

# **Retrofit Electrochromic Glazing: A longitudinal case study of occupant experience**

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Dedicated to the memory of  
Edward Joseph Kelly *1942 – 2014*



## **Abstract**

Electrochromic (EC) glazing has emerged as an alternative to traditional forms of glazing. It has the potential to enable occupants to control daylight ingress without the use of blinds, giving users more access to daylight with all its inherent benefits. Research efforts to date have been mainly focussed on the potential of EC glazing as an energy saving technology through the reduction of electric lighting and air conditioning energy loads, using scale models, computer simulations and full scale test rooms. Few studies have considered the user experience of the technology, and none of the studies that have included data from human participants have been carried out in a real-world research setting over a long-term period. Thus, there is a general lack of understanding regarding the performance and suitability of EC glazing in real-world working environments.

To address this gap in research, a new study of EC glazing was undertaken, looking at the experience of occupants working in an office that had been retrofitted with EC-glazed windows. The retrofit was the first of its kind in the UK, and provided an opportunity to study the user experience of EC glazing in a real-world setting over a longitudinal period. The aims of the study were to gain new insights into the experience of users of EC glazing, and to learn about the practicalities of installing it. A number of research questions were defined, leading to a mixed methods data collection programme, carried out over a period of almost 18 months. The data collection encompassed data from the occupants as well as from the physical environment, and was designed in response to the constraints of the site and occupants, as well as the aims of the research enquiry. The resulting data set includes a valuable record of occupant experiences and behaviour, as well as detailed information about environmental conditions at key times. A number of contextual factors influencing the effectiveness of EC glazing were identified. The outcomes of this research provide a new understanding of the user experience of EC glazing, and thus can inform further technological development and benefit future installations.

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## **Part I      Background**

The focus of this study is on the user experience of electrochromic glazing, with particular reference to visual comfort. The research background thus involves a wide range of aspects, such as the study of daylight in buildings, visual comfort and the need to control daylight ingress, as well as previous studies of electrochromic glazing.

Chapter 1 gives an overview of the benefits of daylight in buildings and the need to control it with shading. The limitations of traditional forms of shading are explained, building the case for “smart” glazing materials with dynamic tint properties (of which electrochromic glazing is one) as a more efficient method of daylight control that has a number of potential benefits to occupants. Electrochromic glazing is then explained in detail in Chapter 2. This chapter contains a literature review of studies of electrochromic glazing, which highlights the gap in research upon which this study is built. The final sections of this chapter outline the scope of the study and its research questions. Chapter 3 examines the methods used to study the control of daylight in buildings, and in particular the interaction between occupants and shading devices. From this literature review, a number of methods are identified for use in this, a new study of electrochromic glazing.

## Chapter 1

# The control of daylight in buildings

### 1.1 The need for daylight in buildings

The study of daylight in buildings, known as daylighting, has become a crucial aspect of sustainable building design. The benefits of daylight are numerous, however they can be described in terms of in three principal aspects: Energy use, aesthetics, and occupant health and wellbeing.

#### *Energy use*

A building that utilises the available daylight is less reliant on electrical lighting. Good daylighting maximises a building's potential for daylight by ensuring that the quantity and distribution of daylight in the interior meets its lighting requirements for as much of the occupied time as possible, given the seasonal and diurnal availability of daylight [CIBSE Lighting Guide 10, 2014]. Measures, such as zoning of electric lighting, appropriate siting of switches, the use of daylight-linked dimmable lighting and informed use of shading devices can be used to ensure that electric lighting is not used when sufficient daylight is available. Technological advances have resulted in improvements in the energy efficiency of lighting systems, meaning that there may be less impetus for energy and cost savings through the reduction of lighting energy use. Nonetheless, a decreased reliance on electric lighting is also desirable for other reasons, as described below.

#### *Aesthetics*

The appeal of daylit spaces is almost universal. Interiors are enlivened by the dynamic nature of sunlight and surfaces are pleasingly modelled by the flow of diffuse daylight. It is widely held that people prefer the feeling of spaciousness afforded by the higher vertical illuminances found in daylit spaces. Several studies have underlined the preference of occupants for windows [*e.g.* Farley &

Veitch, 2001; Collins, 1976], and others, such as Wang & Boubekri [2010] found that, given the opportunity, occupants are more likely to choose a seat close to a sunlight patch in a sunlit room.

### *Occupant health & wellbeing*

In the context of our evolutionary history, it is only recently that humans have come to spend most of their time inside buildings. Thus, it is no surprise that humans are essentially phototropic organisms, whose physiology and psychology is closely linked with the 24-hour light-dark cycle of our planet.

Confirmation of the existence of a non-visual photoreceptor in the human eye at the turn of the century [Brainard *et. al.*, 2001] has led to an increased understanding of the crucial role of daylight exposure to human health. Exposure to daylight at the eye and via the skin affects a wide range of aspects, often referred to as “non-visual effects” since they pertain to functions of the eye other than seeing. The understanding of the mechanisms behind these processes is still being developed. Currently, the list includes:

- Entrainment of the circadian system and its subsequent effects on sleep quality, task performance and long-term effects on the human endocrine system.
- Psychological aspects, such as short term mood and longer term seasonal affective conditions.
- Increased Vitamin D production and blood-pressure-lowering through skin exposure [Opländer *et. al.*, 2009].

A literature review by Aries *et. al.* [2015] highlighted the diversity of the health effects of daylight, but also underlined the lack of specific recommendations to building designers with regards to the quantity of daylight required to elicit these health effects.

In addition to the health aspects described above, there are several wellbeing benefits associated with the ability to see outside through openings in the building envelope. The benefits of a view to outdoors have been widely



documented, especially if those views contain nature elements. Several studies have looked at the restorative effects of views of nature [*e.g.* Leather *et. al.*, 1998; Kaplan, 1995; Ulrich *et. al.*, 1991]. These effects can have a positive impact on absenteeism in workplaces, and on the recovery time of patients in hospital [Ulrich, 1984]. In a typical office building, a view out facilitates restoration and respite from work tasks in the following ways:

1. Reducing eyestrain: A view out allows occupants to rest their eye muscles during screen breaks by focussing on distant objects [Heschong, 2003].
2. Visual stimulus: Activity outside, such as human activity or wildlife, can provide welcome visual interest. A number of studies on the effect of windowlessness on human occupants have reinforced this. One such study, by Heerwagen & Orians [1986], suggests that given the opportunity, individuals in windowless rooms will try to compensate for stimulus deprivation using pictures and other materials.
3. Connection with nature: A view offers a connection to the natural world, through views of natural landscapes or, in a more urban setting, through the ability to gauge localised weather conditions by looking at the sky [Farley & Veitch, 2001].
4. Sense of time: A view to outside can increase occupants' awareness of the time of day and season, giving them a deeper sense of where they are in time (that is, more than that which is provided by a clock). It is also possible that this reinforces the chronobiological mechanisms previously mentioned (*i.e.* circadian entrainment) [Veitch, 2011].

View composition is important, as it dictates the perceived quality of the view and thus the benefits to the wellbeing of the occupant. Typically, an outdoor scene is stratified: the top layer is sky, the middle layer may contain buildings, mountains or vegetation, and the foreground may contain smaller landscape elements, or paved areas animated by vehicles and people. This is an area of interest, to which occupants most often direct their gaze. Ideally, a window view should contain all three of these layers [CIBSE Lighting Guide 10, 2014].

Even if daylight enters a building indirectly (without the possibility of a direct view to outside), occupants will still benefit from an awareness of the time of day and localised weather conditions through changes in colour temperature and intensity [CIBSE Lighting Guide 10, 2014].

## **1.2 Visual comfort**

Evidently, daylight in buildings is desirable for many reasons. However, it is not the case that more daylight leads to better daylighting, since an excess of daylight in a building can lead to a number of problems, such as visual discomfort and overheating. Good daylighting is a balance between the utilisation of available daylight at a particular site and the provision of a comfortable environment for occupants. If comfort needs are not met, occupants may resort to measures that result in the building operating sub-optimally in terms of both energy use and occupant wellbeing, for example by closing window shades and leaving them closed for long periods, thereby effectively removing access to daylight and view out [Aries *et. al.*, 2010]; an issue that will be examined in more detail in the next section.

From the point of view of daylighting, visual discomfort encompasses a range of sensations that can be caused by insufficient light or by an excess of light. Insufficient light will usually result in straining of the ocular muscles in the effort to focus on a given task or object. Excessive brightness in the visual field can result in glare, which can range from uncomfortable to debilitating (*i.e.* preventing task execution). The definition of visual comfort depends upon the context; in some applications (such as in the design of electronic displays), visual comfort is considered as having a separate positive identity to that of visual discomfort. Thus, a number of definitions of visual comfort exist [Boyce, 2003, Chapter 5]. For the purposes of this thesis, visual comfort is defined as the absence of discomfort caused by insufficient light, excessive light, or abrupt variation in brightness within the visual field of an observer.

The potential for visual discomfort is a function of light level and distribution of light in the visual field, and in particular the contrast between the apparent

brightness of neighbouring objects. If the relative brightness of a light source in the visual field of an occupant reaches a critical threshold, an observer may start to experience discomfort glare. The level of discomfort can range from “just perceptible” to “intolerable” [Hopkinson, 1972]. Towards the “intolerable” end of the scale, the glare causes a temporary impairment of vision (disability glare). Visual comfort is dependent on many factors specific to the individual, such as age, eye health, adaptation state of the observer’s eye, and viewing angle.

For sources of artificial lighting, such as luminaires, the distribution and intensity of light output is often highly engineered, and thus predictable and controllable. Hence, the potential for glare from luminaires can usually be quantified for typical applications using some well-known indices, such as the unified glare rating (UGR) [CIE, 1995].

Glare from windows is very different, mainly because the source of glare is large and complex compared to a luminaire, and because the glare sensation elicited by light from windows varies considerably between individuals and is influenced by more numerous factors. For example, the content of the view through the window can increase an individuals’ tolerance to daylight glare [*e.g.* Chauvel *et al.*, 1982; Tuaycharoen & Tregenza, 2007; Shin *et al.*, 2012]. Berman *et al.*’s work [1996] indicated that the spectral content of the light could also be important. Daylight glare can occur under cloudy or clear sky conditions, since it can arise from a bright cloudy sky as well as from direct sunlight. Glare can be caused directly, or indirectly via reflections of the glare source on computer screens, light-coloured surfaces (*e.g.* paper) or reflective surfaces within the room. Acute solar glare can also arise as a result of reflections from adjacent building facades. The objective measurement and prediction of daylight glare is an on-going challenge in visual comfort research, which will be discussed in Chapter 3.

### **1.3 Shading**

The ingress of daylight into a building, and in particular direct sunlight, must be controlled in order to provide a comfortable environment for occupants.

Typically, the two shading functions – glare and overheating – are addressed separately, mainly because they are often required in diametrically opposed seasonal conditions. Shading to prevent solar overheating is typically designed for conditions that arise in the summer months: high solar altitude and increased external air temperature. Shading for glare control, however, is often required most in winter, when solar altitude is low.

Shading for overheating is designed to protect the façade from direct solar irradiation, before it passes through the façade and starts to heat the interior. The usual approach is to try to shade the façade at the high solar altitudes that occur during the summer months. It is important to note, however, that sun penetration is often desirable and beneficial in interiors, especially in winter when it may provide welcome solar heating. Thus, excluding direct sun from the interior all year round is rarely a good strategy, unless there are specific functional reasons for doing so. If fixed solar shading is provided, it is usually in the form of an external element such as an overhang or slatted shading device. There are commonplace examples of non-fixed solar shading elements, such as moveable awnings or external shutters, but these are usually manually controlled and are thus reliant on occupants to use them pre-emptively, *i.e.* before solar irradiation starts to cause overheating. Motorised external solar shading is used less often, mainly because of the expense associated with installation and maintenance. More detail about different types of solar shading can be found in CIBSE Lighting Guide 10 [2014].

Shading for glare control is usually provided internally, using roller shades or slatted blinds. However, it may also be external, incorporated within a double skin façade, or integral to the window (as in the case of inter-pane blinds). Most commonly, shades are manually controlled. One of the main disadvantages of manual shades is the common phenomenon known as “blinds down, lights on”, whereby occupants close shades to deal with a glare condition, but do not open them again once that condition has passed. As a result, blinds are often left closed for long periods, meaning that occupants lose the benefits of both daylight exposure and view through the glazing, and that electric lighting energy use is increased. Several studies of manually controlled blinds found that blind usage

was not consistently related to measured lighting conditions, and that shades were frequently left in a closed position for periods of weeks or even months [e.g. Rubin *et. al.*, 1978; Inoue, 1988; Foster & Oreszczyn, 2001; Inkarorjit, 2008; Van Den Wymelenberg, 2012]. Furthermore, blinds may be opened or closed for reasons other than shading, such as privacy [e.g. Foster & Oreszczyn, 2001].

The solution to this problem seems obvious: Automate the shading system so that it operates in a way that preserves the contribution of daylight as much as possible and allows a view out for occupants more of the time. However, this solution usually involves motorised façade elements that can add significantly to the complexity and cost of construction and maintenance. The Arab World Institute, Paris, is an example of a dynamic shading solution that did not fulfil its potential due to these issues. The south façade, which features decorative Islamic-inspired panels with circular openings that dilate and contract in an iris-like movement, has sadly failed to perform due to a lack of maintenance [Meaghar, 2015]. In addition, there is the difficulty of designing a control algorithm that satisfactorily matches the needs of occupants. As mentioned above, many studies of occupant interaction with manual blinds have generally not been able to establish a consistent relationship between manual blind usage and measured external or internal lighting conditions. These complexities have made the task of developing a satisfactory model of how occupants use shading especially difficult [Van Den Wymelenberg, 2012]. This is even more so in multiple-occupant spaces, where the system is required to meet the needs of a range of individuals. Shared spaces also introduce further complexity in terms of occupant behaviour, since the presence of other occupants can influence the behaviour of an individual via a variety of social and psychological mechanisms [Yan *et. al.*, 2015; O'Brien & Gunay, 2014]. Nonetheless, a literature review of studies of occupant interaction with shading devices (see Chapter 3) indicates that few studies have considered the effect of multi-occupant spaces on user behaviour.

Site-specific refinement of control system settings is necessary to optimise the control regime to suit the needs of a particular user group, as noted in a number of post occupancy studies with automated shading [e.g. Lee *et. al.*, 2013]. Trust in

automation is also a key factor; the level to which an occupant trusts an automated system (be it shading, air conditioning, lighting etc.) to provide comfortable conditions in their workplace can significantly influence the degree of user acceptance [Xu *et. al.*, 2014]. As a result of these issues, even where automated shading has been applied sensitively, occupants still report a considerable level of dissatisfaction due to glare problems [*e.g.* Konis, 2013; Lee *et. al.*, 2013].

The methods used to study the way in which occupants interact with shading in office buildings are discussed in Chapter 3.

## **1.4 Glazing-based daylight control**

In addition to the traditional shading devices described above, there are a variety of glazing-based solutions, which can be static or dynamic. Dynamic types are often referred to as “smart” or advanced glazing materials, of which electrochromic glazing is one.

### **1.4.1 Tinted glazing**

The static types are glazing materials in which the glass has undergone a treatment during manufacture, or onto which a film or coating has been applied. The primary objective of such treatments is to reduce light transmittance, both in the visible part of the spectrum and at the infrared end, in order to reduce solar heat gain. As such, these types of glazing materials are usually aimed at controlling solar heat gain rather than glare, and some additional form of shading is usually required to provide visual comfort. Treatments include tinting, ceramic printing (or “fritting”) and prismatic coatings or films.

From the point of view of glare control, these materials are limited by the fact that they are optimised for one set of conditions. The solar disc has a luminance in the region of  $10^9$  cd/m<sup>2</sup>, and thus sufficient control of glare in a static glazing material could only be achieved by heavily tinting the glass, resulting in a permanently distorted view through the window.

In the 1970s and 80s, tinted glazing became widespread in an attempt to reduce solar heat gain in highly glazed office buildings. The colour of the tint was typically bronze, but blues and greys were also common. During the past 20 years, advances in glazing coatings, such as low emissivity (or “low-e”), have resulted in glazing materials that are spectrally selective without being visibly tinted. As a result, tinted glazing is rarely employed as part of a shading strategy in contemporary buildings. Nonetheless, studies of tinted glazing are a relevant part of this discussion, since variable tint glazing materials such as electrochromic glazing have similar properties in their tinted states.

Tinted glass is made by adding metal oxides to the batch mix to give a uniform coloured tint to the glass. Typical colours for body-tinted glass are green, grey, bronze and blue. The amount of tinting must be balanced with the needs of the occupants; tinting below a visible transmittance of around 30% is considered unsatisfactory as it can make the interior appear gloomy and impair the view out [Boyce *et. al.*, 1995]. The colour of tint is important, not only from the point of view of solar heat gain reduction, but also for user acceptance. A small number of studies have suggested a preference for certain glazing colours, and that different colours can elicit different non-visual effects [Cuttle, 1979; Arsenault *et. al.*, 2012; Hraska *et. al.*, 2014].

Cuttle [1979] used a scale model and a novel liquid-based filter that could simulate a range of different glazing colours. His work indicated a preference for non-neutral glass that gives a warm shift (bronze), which is consistent with the findings of other research indicating a general preference for warm colours in interiors. However, this may be linked to the climate in which the participants are located, with cooler climates leading to a preference for warmer coloured interiors, and vice versa. Arsenault *et. al.* [2012] studied the human response to glazing with three tinted colours (blue tint, bronze tint, and neutral) using a scale model of a cellular office. The results indicated that bronze tinted glazing was preferred, echoing Cuttle’s findings. However, it was also found that blue tinted glazing resulted in a reduced alertness level. The same effect was also indicated by Hraska *et. al.*’s [2014] small study of six dementia patients in hospital rooms, who monitored the circadian light exposure and melatonin levels of patients in

two rooms, one with windows that were fitted with an amber filter, and the other with windows that had no filter applied. They found that patients in the room with the amber tinted windows had more pronounced levels of melatonin suppression than those without, pointing to a possible alerting effect of bronze or amber daylight filters. This is the opposite of general understanding of artificial blue light or blue-enhanced light, which is understood to increase alertness by suppressing melatonin production [*e.g.* Iskra-Golec *et. al.*, 2012]. Intriguingly, this suggests that if daylight enters a space through what is effectively a blue filter, it has the opposite effect on occupants than if the light source itself has a significant blue spectral content.

The methods used in these studies to collect data from participants are discussed in Chapter 3.

#### **1.4.2 Variable transmission glazing (VTG)**

The disadvantages of manually controlled shades, coupled with the expense and relative complexity of motorised shades, make a dynamically tint-able glazing material highly desirable. From the point of view of visual comfort, a glazing with a visible transmittance that varies continuously between fully transparent and tinted extremes could offer a much greater degree of control over the luminous environment than traditional shutter-like shading devices such as window blinds. In addition, such a material could allow a view out continuously, even when the glazing is in its most tinted state. During the past two decades, a number of glazing materials have emerged that have these properties. They are often referred to as “smart” glazing materials because of their potential as part of climate-adaptive building envelopes. A more precise term is variable transmission glazing (VTG). The principle behind VTG is straightforward: the optical properties of the glazing are varied to optimise the luminous and/or thermal environment.

The key to performance for a VTG is a high visible transmittance in the clear state and a sufficiently low visible transmittance in the darkened (or tinted) state. To be perceived as acceptable to the majority of building occupants, the



VTG in the clear state should appear like ordinary (un-tinted) double glazing, and so have a visible transmittance of 60% or greater. In the darkened state, the transmittance should be low enough so that additional shading is required only very rarely, or perhaps not at all. In practice, this means a minimum visible transmittance of around 2% or less [Lee, 2006].

It is widely understood that users value the ability to manually override automated systems, and that a lack of manual control can contribute to considerable dissatisfaction with such systems [*e.g.* Bordass *et. al.*, 1993]. Thus, to be acceptable to users, VTG should be manually controllable by occupants in addition to automatic operation governed by a control system. Another important feature for user acceptance is the transition time: the time it takes for the glazing to change from one tint-state to another. Instantaneous or near-instantaneous switching is desirable for manual control, but not when the glazing is being controlled automatically, due to the potential for distraction. Gradual transition is more desirable for automatic control, but does not give occupants the ability to provide immediate shading from glare. Therefore, a fine balance must be achieved in an ideal system. Lastly, the colour of the glazing in its tinted state is important, since it effectively acts as a filter to the daylight entering the room. This has an impact on both the visual appearance of colours in the room and the view through the glass to outside. Thus, the colour of the glass could affect user acceptance and contribute to certain psychological and physiological phenomena, such as alertness or mood. As yet, no studies have been carried out to compare the user experience of VTG with different tint colours.

There are several types of VTG. For the purposes of this discussion, they will be split into two main groups: Chromogenic materials and non-chromogenic materials.

### *Non-chromogenic materials*

The non-chromogenic materials include suspended particle devices, liquid crystal devices and micro-electromechanical systems. In a suspended particle

device (SPD), a film applied to the glass contains a suspension of rod-like particles in billions of liquid droplets. An applied voltage alters the orientation of the particles and therefore the transmission properties of the film, and the transition happens instantaneously when the circuit is closed. SPD films have become popular in the automotive sector for use in rear windows and sunroofs, and have been successfully used for passenger aircraft windows in place of manual blinds. As an architectural element, however, SPD glass is of limited use because of the currently available range of transmittances, and particularly its low transmittance in the clear state [Baetens *et. al.*, 2010].

Polymer-dispersed liquid crystal (PDLC) glazing operates in a similar manner, but is fundamentally different in its coloured state, which is translucent (“milky”) rather than tinted. PDLC glazing contains liquid crystals suspended in a polymer, held between two layers of transparent material. When no voltage is applied, the crystals are arranged randomly, resulting in a scattering of light as it passes through the glass. Upon application of voltage, the crystals align, allowing light to pass through. This type of glazing provides opacity rather than tinting. PDLC glass has been available on the market for some years, primarily for use as switchable privacy glass, such as for internal partitions or for isolated sections of glazing that are not suitable for blinds or curtains due to inaccessibility. As a façade glazing material, however, it is of limited benefit. It is not suitable as a solar shading technology since, in direct sun, the translucency could lead to the window becoming extremely bright (and thus a secondary glare source). PDLC glass also has some long-term UV stability issues [Jelle *et. al.*, 2012].

Micro-electromechanical systems (MEMS) have tiny, micron-scale structures that move in response to an applied electrostatic field, thereby altering the transmission properties of the glazing. Other electromechanical systems have been devised, but at the time of writing, these technologies are still undergoing development, and although prototypes are available, they are yet to move into commercial viability.

### *Chromogenic materials*

Chromogenic glazing materials have four distinct types of formulations for coatings that have variable transmittance properties [Baetens *et. al.*, 2010]. Each type of chromogenic glazing has a different input variable, *i.e.* the parameter that is controlled in order to trigger a change in the transmittance of the glazing. The types of chromogenic glazing and their input variables are shown in Table 1.1.

**Table 1.1      Types of chromogenic glazing**

<b>Glazing type</b>	<b>Input variable</b>
Electrochromic	Voltage
Gasochromic	Concentration of pumped gas
Photochromic	Localised illumination
Thermochromic	Localised temperature

In chromogenic devices, the change in transmittance is a chemical process that does not happen in all parts of the coating simultaneously. It is a gradual process, and therefore takes time (of the order of minutes) to complete the transition between one tint-state and another. Transition time is affected by local ambient temperature (with increased transition time at lower ambient temperatures) and size (with greater areas having a longer transition time). As the visible transmittance varies, so does the solar heat gain coefficient. Thus, variable heat gain control is another advantage of such a material, particularly because the control happens at façade level, before the heat gain has entered the space.

Thermochromic and photochromic glass are essentially passive devices which respond to changes in the environment, whereas electrochromic and gasochromic glass are active devices that can be configured to respond to any sensor input, such as illumination, temperature, or some combination of the two. There are examples of thermochromic glazing on the market, though the narrow visible transmission range indicates that additional shading would be needed to control glare. Thermochromic glazing therefore seems better suited to offering a degree of moderation of the thermal rather than the luminous environment. Photochromic coatings have been used successfully in eyeglasses for some time,

but have not yet found a place in the market as a façade glazing material. Gasochromic glazing can be actively rather than passively controlled, and has the potential advantage of faster transition time. The main disadvantage is with regards to installation, since a gasochromic system requires that the glazing unit be connected to an electrolyser and pump by piping. The practicalities of a gasochromic installation are such that the technology is still considered the preserve of research.

Electrochromic (EC) glazing offers the possibility of active control without the complexity of installation associated with gasochromic glazing. It also offers a large range in glazing transmittance, making it well suited as a VTG façade element. Of the technologies described above, EC glazing is considered to be the most promising as an architectural glazing material [Jelle *et. al.*, 2012; Baetens *et. al.*, 2010]. EC glazing will be described in detail in the next section.

Table 1.2 provides a summary of currently available VTG materials. Cost has not been included in this analysis, primarily due to the difficulty of obtaining cost information in a format that allows direct comparison between technologies. Also, as some of these technologies are not currently commercially available, only speculative cost information, if any, is available.

**Table 1.2 Overview of VTG materials for architectural glazing**

VTG type		Strengths	Weaknesses
Chromogenic	Electrochromic	<ul style="list-style-type: none"> <li>• Wide transmittance range</li> <li>• Straightforward to install</li> <li>• Needs power supply only when switching</li> <li>• Active control</li> </ul>	<ul style="list-style-type: none"> <li>• Transition time can be slow</li> </ul>
	Gasochromic	<ul style="list-style-type: none"> <li>• Short transition time</li> <li>• Active control</li> </ul>	<ul style="list-style-type: none"> <li>• Installation (plumbing)</li> <li>• Limited transmittance range</li> </ul>
	Photochromic	<ul style="list-style-type: none"> <li>• Straightforward to install</li> </ul>	<ul style="list-style-type: none"> <li>• Passive control only</li> </ul>
	Thermochromic	<ul style="list-style-type: none"> <li>• Straightforward to install</li> </ul>	<ul style="list-style-type: none"> <li>• Passive control only</li> <li>• Limited transmittance range</li> </ul>
Non-chromogenic	SPD	<ul style="list-style-type: none"> <li>• Straightforward to install</li> <li>• Instant switching</li> </ul>	<ul style="list-style-type: none"> <li>• Instantaneous switching less suitable for automatic control</li> <li>• Limited transmittance range</li> <li>• Needs constant power supply in clear state</li> </ul>
	PDLC	<ul style="list-style-type: none"> <li>• Straightforward to install</li> <li>• Instant switching</li> </ul>	<ul style="list-style-type: none"> <li>• Provides opacity rather than tinting</li> <li>• UV stability issues</li> <li>• Needs constant power supply in clear state</li> </ul>
	MEMS	Under development	

## 1.5 Summary

The importance of daylight in buildings is widely understood. However, the ingress of daylight must be controlled in order to ensure that occupants' visual comfort needs are met. This is difficult to achieve with manual shading without compromising access to daylight and views. Automated shading solutions, involving motorised façade elements, can increase complexity and result in on-going issues of access and maintenance.

A glazing material that enables dynamic control of daylight ingress whilst maintaining the view out, and without the need for moving parts, is thus highly desirable. VTG materials offer such a solution and, of these, EC glazing has a number of characteristics that make it well suited as a glazing element that could provide visual (and thermal) comfort without the need for additional shading.

## Chapter 2

### Electrochromic glazing and the need for a new study

Electrochromic (EC) glazing is considered to be one of the most promising of the variable tint glazing materials that are currently available, as explained in Chapter 1. This chapter takes a more detailed look at EC glazing, describing how its operation and functional characteristics as a fenestration material. This is followed by a review of previous studies of EC glazing, identifying the gap in research upon which this study is built.

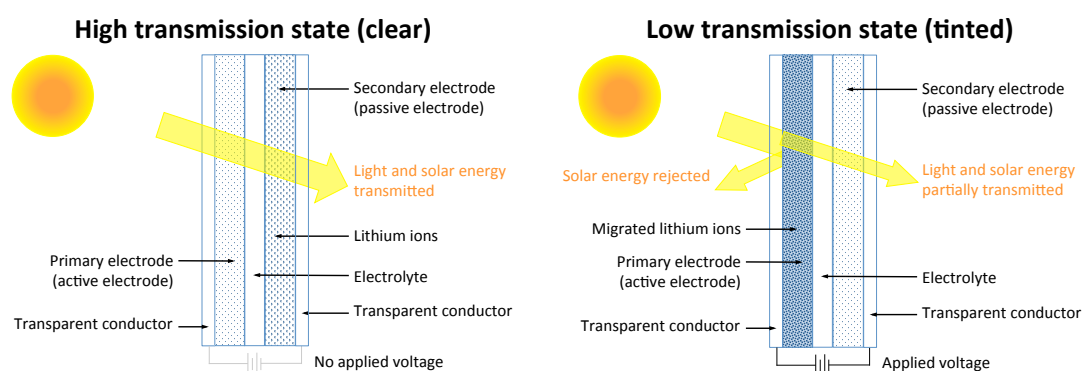
#### 2.1 Electrochromism and electrochromic glazing

Electrochromism can be defined as a reversible colour change in a material caused by an applied electric field or current [Lampert, 1984]. Typically, the change is from colourless to coloured and vice versa. The phenomenon has been known since the 19<sup>th</sup> Century [Mortimer, 2013], but it was only in the latter part of the 20<sup>th</sup> century that scientists began to study the electrochromic properties of transition metal oxides and develop electrochromic films that could be applied to other materials, such as glass, for a variety of purposes [Deb, 1973]. Electrochromic (EC) materials have a diverse range of applications, including displays, photovoltaics, automotive (rear-view mirrors) and even as a medical diagnostic tool [De Matteis *et. al.*, 2016]. The potential of EC glass as an architectural glazing material has been investigated since the 1980s [Lampert, 1984; Svensson & Granqvist, 1984]. However, it is only since the turn of the 21<sup>st</sup> century, with major new investment and scaled-up production, that EC glazing has become a commercially available product [Lee & DiBartolomeo, 2002].

In a double glazed EC window, an electrochromic coating is usually applied to the inner surface of the outer pane (“surface 2”) during window manufacture. The glass can be coated using a number of methods, such as sputtering, electro-deposition or lamination.

The choice of coating method affects the cost of production as well as the durability of the end product. Sputtering is widely used in the glass industry for the application of coatings (such as low-e, spectrally selective, etc.), and thus is well proven. Electro-deposition could be significantly cheaper than sputtering [Wang *et. al.*, 2013], but is less established as a coating method. Lamination has the advantage of being capable of producing flexible coatings, *i.e.* in the form of an electrochromic foil [Granqvist, 2012], which can be applied to glazing retrospectively in-situ as part of a window renovation programme. In theory at least, an electrochromic foil such as this could also be applied to a flexible transparent material, such as ethylene tetrafluoroethylene (ETFE), creating a truly dynamic building envelope.

The durability of EC glazing depends on a number of factors, including the coating process, the range of ambient temperatures and level of UV exposure to which the glazing is subjected in its application. Durability is usually tested using accelerated techniques such as rapid voltage cycling as well as exposure to extremes of temperature and UV exposure. Figure 2.1 shows how the coating operates in its tinted and un-tinted (clear) states.



**Figure 2.1** Cross section through the EC coating in the clear and tinted states. The coating is extremely thin (of the order of 2 microns thick). Image redrawn with permission from Lawrence Berkeley National Laboratory.

The coating is made up of five layers, with the outer layers being transparent conductors. The three inner layers behave somewhat like a battery, comprising of two electrode layers separated by an electrolyte. A voltage of less than 5V DC

is required to cause the migration of ions (in the case shown above, lithium,  $\text{Li}^+$ ) from the electrochromic layer to the counter electrode layer via the electrolyte.

There are a large number of chemical compounds that display electrochromic behaviour, *i.e.* changes in optical properties upon the addition or removal of electrons. The list includes a wide range of organic and inorganic compounds; Mortimer *et. al.* [2015] gives a comprehensive list. For reasons of chemical stability, particularly with regard to UV degradation, electrochromic glazing usually employs inorganic substances; typically a transition metal oxide, such as tungsten oxide ( $\text{WO}_3$ ). Other inorganic compounds such as Prussian blue (indium or iron hexacyanoferrate) are also commonly used. Electrodes are often comprised of a mixture of two or more different compounds, which enables the formulation to be more finely tuned to the application.

In electrochromic windows, the primary electrode is usually “cathodic”, *i.e.* colours upon ion insertion, whilst the secondary electrode is usually “anodic”, *i.e.* colours upon ion extraction. In this way, the two electrodes have complementary properties, which can reinforce the colouring process, *i.e.* so that a deeper tint can be achieved. Figure 2.2 shows the main part of the periodic table of elements in which the transition metals are highlighted whose oxides display electrochromic properties upon ion insertion or extraction.

**ELECTROCHROMIC OXIDES:**

H																			He
Li	Be												B	C	N	O	F	Ne	
Na	Mg												Al	Si	P	S	Cl	Ar	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe		
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn		
Fr	Ra	Ac																	

**Cathodic coloration**

**Anodic coloration**

**Figure 2.2** Periodic table showing transition metals whose oxides display “cathodic” or “anodic” electrochromism. Reproduced with permission from Granqvist [2012] © 2011 Elsevier B.V.



Different formulations result in differences in the colour appearance of the glass, both in the tinted and clear state. The mechanisms behind the colouration of electrochromic compounds are not fully understood, but it is generally thought to be due to the shape of the crystalline structure. In cathodic metal oxides, the octahedral shape of the molecules and the way in which they join together results in key energy band gaps in the molecules, giving the material its transparency. Upon ion insertion, the crystalline structure is distorted, resulting in optical absorption of all but certain wavelengths of visible light and the appearance of a dominant colour. Hence, different compounds produce different colours, and various mixes of compounds can be created to achieve absorption in specific areas of the visible spectrum. In the case of EC windows, it is usually desirable to formulate a material that exhibits more spectrally even absorption, resulting in a more neutral colour when the glazing is tinted. The chemistry of electrochromism is covered in depth by Mortimer *et. al.* [2015].

## **2.2 Studies of EC glazing**

The body of research into EC glass as a fenestration material is mostly comprised of computer simulation-based studies that focussed on the energy saving benefits, with a limited number of physical studies, only a few of which included human participants (and thus considered the impact of EC glazing on occupants). The physical studies include scale models, full-sized purpose-built test rooms and one published post occupancy study.

### **2.2.1 Computer simulation studies**

Early research into EC glazing focussed on computer simulations that signalled the potential energy-saving benefits of EC glazing [Sullivan *et. al.*, 1994; Moeck *et. al.*, 1998]. Simulation studies, being much easier and cheaper to implement than physical studies, have continued to make up the bulk of research into EC glazing [*e.g.* Fernandes *et. al.*, 2003; Assimakopoulos *et. al.*, 2007; James & Bahaj, 2005; Gugliermetti & Bisegna, 2003; Karlsson *et. al.*, 2001].

Some of these studies [Assimakopoulos *et al.*, 2007; Gugliermetti & Bisegna, 2003] focussed on the optimisation of the EC glazing control algorithm. Gugliermetti & Bisegna's results suggested that visual comfort-based control could be at odds with the intention of controlling for maximum energy saving, since the need to make maximum use of available daylight to light the space, thereby reducing lighting energy, can conflict with the need to control daylight to avoid visual discomfort. Assimakopoulos *et al.* [2007] compared a number of different strategies for controlling EC glazing using a physical test cell and computer simulations. The main conclusion is that on-off control (compared with a fuzzy logic based algorithm) based on an indoor horizontal illuminance setpoint performs best in terms of overall energy consumption (heating, cooling and lighting). However, both of these studies were based in Mediterranean locations, and it is therefore not certain that the findings would be supported in a more northerly, heating-dominated climate. Fernandes *et al.* [2013] performed a simulation study of split pane EC window with venetian blinds in a cellular office in California, comparing the EC window with blinds to a reference case of a clear window with blinds. The simulations were performed with hourly blind control and then daily blind control, which is arguably more realistic. It was found that EC glazing with blinds consumed more lighting energy than clear glazing with blinds when hourly blind control was used. However, when daily blind control was used, EC glazing with blinds resulted in lower lighting energy consumption.

In general, the results of simulation studies have indicated the potential of EC glazing to lower cooling energy use by reducing solar overheating, and to reduce electrical lighting energy by avoiding the "blinds down, lights on" scenario. However, the accuracy of computer models is limited by a number of assumptions about weather conditions, building fabric, visual comfort thresholds and user control of the EC glazing. The latter point is a particular weakness of computer models due to the challenge of accurately modelling user behaviour [Da Silva *et al.*, 2012], *i.e.* when and how users might manually override the automatic settings determined by the control algorithm. Thus, physical studies were needed to model the control behaviour of EC glazing more accurately and allow the inclusion of human participants (and thus the effect of user behaviour on energy usage as well as the issue of user acceptance).

### 2.2.2 Physical studies

In the late 1990s, EC glazing prototypes began to emerge [Pennisi *et. al.*, 1999; Wittkopf *et. al.*, 1999]. This was followed by a number of physical studies, some of which used reduced scale models, others based in full-sized test rooms and one that was based in real-world setting. A small number of studies included human participants, the results of which are discussed here (with the methods used discussed in Chapter 3).

The studies are discussed in the paragraphs below, followed by a summary of these studies and their main conclusions in Table 2.1.

#### *Scale model studies*

Piccolo and colleagues conducted a series of studies of an EC glazing prototype (with a minimum visible transmittance of 7%) in a reduced scale test room in southern Italy, based on physical measurements and computer simulations. The first studies [Piccolo *et. al.*, 2009 (1); Piccolo *et. al.*, 2009 (2)] focussed on the performance in terms of daylighting and glare control, based on a range of calculated glare indices. Results indicated that the EC glazing could control glare from high luminance sky patches effectively, but that it may not be able to fully address glare from direct sun. A third study [Piccolo, 2010] evaluated the thermal performance during the summer, and concluded that the EC glazing significantly reduced the cooling load when compared with un-shaded clear double-glazing.

#### *Studies based in full-sized test rooms*

In work published since the early 2000s, researchers at Lawrence Berkeley National Laboratories (LBNL), California, conducted several studies of EC glazing in a full-scale test cell. The work focussed on a particular product, manufactured by SAGE Electrochromics Inc. Lee & DiBartolomeo [2002] studied an EC glazing prototype with a visible transmittance range of 11 - 38%. Three full-scale test rooms were used to compare static clear glazing, static tinted glazing and EC glazing. The façade of the test cells was south facing, and the test period was

limited to some winter days when solar altitude was low. The results indicated that the EC window performed well as a controller of window luminance. As there were no human participants, the potential for glare was calculated using the subjective rating (SR) index [Osterhaus, 1996]. (Refer to Chapter 3 for a discussion of daylight glare metrics). The results suggested that a minimum transmittance of around 1% could reduce window luminance to comfortable levels. The results also indicated that on clear sunny days, there may be a conflict between the need to reduce glare and the need to provide as much daylight as possible for lighting energy saving, echoing Gugliermetti & Bisegna [2003]. Daily lighting energy use was, depending on the weather, 3% less than clear glazing with blinds, or 13% more. The issue of response time was discussed, noting the tendency for low ambient temperature to significantly increase the time taken for the glass to transition from a fully un-tinted to a fully coloured state. The authors surmised that this could be a source of annoyance for users who have a need to resolve their visual discomfort quickly in order to continue working. Another point raised in the discussion was that of privacy, since EC glazing might not provide the level of privacy desired by occupants in situations where this is a requirement.

Later, Lee *et. al.* [2006] used a similar test cell arrangement to study an EC glazing with a visible transmittance range of 5-60%, this time during September. Each room was fitted with a daylight-linked electric lighting system. Tests were carried out to see the effect on electric lighting energy use and its ability to control the illuminance level on the workplane within a control set-point range. The study reported significant savings in electric lighting energy with EC glazing compared with the reference cases, with daily lighting energy savings of 8-23% compared to the reference window, which had a visible transmittance of 50%. The integrated window-lighting control system maintained interior illuminance levels to within 10% of the set-point range of 510-700 lx for 89-99% of the day. These more positive results are likely to be due to the improved range of visible transmittance, but also due to the tuning of the control algorithm.

These studies indicate that EC glazing holds significant potential as a means of improving daylighting and lowering energy consumption through reductions in

lighting and air conditioning use. However, as with any energy-saving technology, its success is heavily dependant on the level of acceptance of building occupants and how they interact with it. Thus, there was a need to evaluate the subjective experience of EC glazing, for example to record occupants' experiences of visual comfort, rather than relying on calculated indices. In 2006, two lab-based studies were published which included human participants [Clear *et. al.*, 2006; Zinzi, 2006].

In Clear *et. al.*'s study, 43 participants were invited to spend one hour at a time in a test room that had a large south-facing EC window with a transmittance range of 3-60% (manufactured by SAGE Electrochromics Inc.). The windows were fitted with venetian blinds and dimmable electric lighting. During each session, one of three different control protocols was tested. Participants determined their preferred target workplane illuminance using a software interface on a computer, and were allowed to manually control the venetian blinds if they desired. Afterwards, they were asked to complete a questionnaire about their experience in the room. The tests took place in California in winter (November – March) when sun altitude was low, giving rise to visible direct sun on clear days. The results indicated a good level of user acceptance, with blinds used less when the EC glazing was being automatically controlled compared with when the EC glazing remained un-tinted. The study also found that participants used slightly more electric lighting when the EC glazing was automatically controlled. More than half of participants indicated that they would prefer the glass to be able to tint to a darker level than that which was available, suggesting that a visible transmittance lower than 3% is necessary for the EC glass to be able to control direct sun satisfactorily. This finding supports previous studies [Gugliermetti & Bisegna, 2003; Lee & DiBartolomeo, 2002], which indicated that a minimum transmittance lower than 3% was desirable. Clear's work also concluded that the ability to control individual panes separately would be beneficial, for example to control glare through the lower portion of the window whilst allowing daylight to enter through the upper part. This could counteract the increase in lighting energy use that resulted when the EC windows were being tinted to control glare.

In Zinzi's study [2006], a test room contained two EC windows on two different facades, one facing north and the other facing west. The glazing used in Zinzi's study had a relatively narrow range of visible transmittance, with a maximum of 50% and a minimum of 15%. The windows were fitted with manually controlled translucent roller blinds and the room had dimmable electric lighting. The tests were carried out in Rome between August and October, when direct sun would be visible from within the room. 30 participants were invited to the room for one-hour periods, during which time they were asked to adjust the EC window, lighting and blind to suit their requirements and to complete a questionnaire. Half of Zinzi's participants used the blinds in addition to the EC window to improve their lighting conditions. The majority of these had already set the window to its maximum tint level. This is not surprising considering that a minimum transmittance of only 15% was possible. The main issue raised by Zinzi's results is that of switching speed, and in particular the time taken for the window to transition from clear or tinted. The glazing used in Zinzi's study took about 12 minutes to complete the transition, and this was cited by a number of participants as being a problem.

In 2013, Zarkadis & Morel published a study based in a test room fitted with a compound window that contained a daylight redirection system (anidolic) in the upper zone and EC glazing in the lower zone with a visible transmittance range of 15 – 55%. The windows in the test room were also fitted with blinds. The data collection included measurements of physical conditions in the room, a short survey of nine participants who each spent two hours in the room, and computer simulations to evaluate a number of different theoretical window types and two different EC window control algorithms. The first EC control algorithm was a simple closed-loop based on internal illuminance, and the second was a more complex regime that involved the use of a novel sky-scanner, made up of a fish-eye webcam aimed at the southern sky combined with a fuzzy logic learning algorithm. The results suggest that the latter control algorithm did not produce significant benefits compared with the simpler one, from the point of view of energy consumption or visual comfort. The survey results indicated dissatisfaction with colour rendering, and a need to use blinds to control glare because the EC glazing alone was not sufficient. The latter finding is not

surprising given that the minimum transmittance of the glazing was still quite high, at 15%.

More recently, a study was conducted in Shanghai, China [Li *et al.*, 2015], which involved 84 participants. The study used two meeting rooms in an office building as the location for a series of tests with the participants (*i.e.* not the normal occupants of the rooms). One room was fitted with EC glazing manufactured by SAGE Electrochromics Inc., with a transmittance range of 1 – 59%. In the other room, standard low-e glazing was fitted to create a reference condition. Both rooms had roller blinds fitted. Participants were asked to complete a series of tasks in the rooms for one-hour periods, and complete a questionnaire that was based on Clear *et al.* [2006]. The methodology used in this study and its results were not clearly explained, however the results indicated satisfaction with the EC glazing in most regards, except for the speed of tinting.

Table 2.1 provides a summary of physical studies (scale models, full sized test rooms and real-world) of EC glazing and their main findings.

**Table 2.1** Summary of previous physical studies of EC glazing

Study	Setting	EC glazing transmittance range	Human participants	Main findings
Piccolo <i>et. al.</i> , 2009 (1 & 2)	Scale model	7 – 70%	None	<ul style="list-style-type: none"> <li>EC glazing can control glare from high luminance sky patches effectively, but may not be able to fully address glare from direct sun.</li> </ul>
Piccolo, 2010	Scale model	7 – 70%	None	<ul style="list-style-type: none"> <li>EC glazing can reduce the cooling load when compared with un-shaded clear double-glazing.</li> </ul>
Lee & DiBartolomeo, 2002	Test room	11 - 38%	None	<ul style="list-style-type: none"> <li>Glare calculations suggest a minimum transmittance of around 1% could reduce window luminance to comfortable levels.</li> <li>On a clear sunny day, there may be a conflict between the need to reduce glare and the need for energy saving.</li> </ul>
Lee <i>et al.</i> , 2006	Test room	5 - 60%	None	<ul style="list-style-type: none"> <li>Daily lighting energy savings of 8–23% compared to reference window.</li> <li>EC window and daylight linked lighting controls maintained interior illuminance to within 10% of setpoint range of for most of the day.</li> </ul>
Clear <i>et. al.</i> , 2006	Test room	3 – 60%	43	<ul style="list-style-type: none"> <li>Participants used blinds less and electric lighting more when the EC glazing was being automatically controlled.</li> <li>More than half of participants would prefer the glass to be able to tint more.</li> <li>The ability to control individual panes separately would be beneficial.</li> </ul>
Zinzi, 2006	Test room	15 – 50%	30	<ul style="list-style-type: none"> <li>Half of participants used blinds in addition to the EC window.</li> <li>Transition time (in this case 12 minutes) was cited as being problematic.</li> </ul>
Lee <i>et al.</i> 2012	Real-world (conference room)	3 – 50%	Variable occupancy, no self-report data collected	<ul style="list-style-type: none"> <li>Significant energy savings made as a result of the window retrofit</li> <li>Performance of EC window was in line with manufacturer's claims.</li> <li>Manual controls were not used very often and some used the switches to admit more daylight than that provided by the automatic system.</li> <li>Blinds were never fully lowered, indicating that the EC window provided good control of discomfort glare without the need for blinds.</li> </ul>
Zarkadis & Morel, 2013	Test room	15 – 55%	9	<ul style="list-style-type: none"> <li>Closed-loop control based on internal illuminance was as effective as a more sophisticated regime using fuzzy logic learning algorithm.</li> <li>Survey results indicated dissatisfaction with colour rendering and a need to use blinds in addition to EC window to control glare.</li> </ul>
Li <i>et al.</i> , 2015	Test room	1 – 59%	84	<ul style="list-style-type: none"> <li>Survey results indicated satisfaction with the EC glazing in most regards except for the speed of tinting.</li> </ul>



Whilst these studies provide valuable insights into the subjective experience of would-be occupants, the findings are ultimately limited to a lab-based setting and cannot be readily extrapolated to real buildings without further research. The participants in these studies experienced EC windows for restricted periods of time (of the order of hours) during one particular season, which leads to a number of limitations:

- The results are affected by the time of day when each test session took place, *i.e.* sun position and localised weather conditions.
- The time of year when the tests took place is similarly important. If tests did not take place throughout the year, then there is a risk that the results are not applicable to a full range of sun positions and weather conditions.
- The participants themselves will have different perceptions on different days depending on a variety of factors, such as mood and alertness. The perceptions captured during these “snap shots” may not accurately reflect their experiences over longer periods of time.
- Within these short time periods, it is likely that the windows were still perceived as a novelty, and that this in turn influenced participants’ perceptions.

Furthermore, there is the question of how the setting may have influenced participants’ experiences. For example, how different were the rooms from participants’ normal workspaces, and how different were the tasks carried out by participants compared to their normal work tasks? One significant difference could result from the fact that the test rooms were set up as one-person offices, where the single occupant determines control over their lighting conditions. Thus, the findings cannot readily translate to an open plan office shared between two or more individuals, who might have different preferences. It is also notable that several of these studies were carried out in climate regions that are cooling-dominated, limiting the validity of the results in more northerly, heating-dominated locations.

### 2.2.3 Real-world studies

At the time of writing, Lee *et. al.* [2012] was the only published field study of EC glazing. This was a longitudinal study of a conference room in Washington DC whose large west-facing glazing had been retrofitted with double-glazed EC windows. The windows were manufactured by SAGE Electrochromics Inc., and had a visible transmittance range of 3% - 50%. The glazing could be set to fully clear or fully tinted, and was controlled automatically with manual override control using wall-mounted switches. The glazing was divided into an upper and lower control zone, with the lower zone having a more conservative threshold to tint than the upper zone in order to reduce the likelihood of discomfort glare for seated occupants. The data collection included measurements of lighting and temperature conditions in the room and monitoring of EC window manual controls and blinds usage. Computer simulations were carried out to enable comparison of energy consumption between EC windows and the previously installed windows. As it was a conference room, the space did not have a regular occupancy pattern, and user feedback was not collected in this study. Some of the physical measurements were used to independently verify the values reported by the EC window control system, for example, glazing transmittance as a function of time. Since subjective data about discomfort glare were not collected, the likelihood of glare was estimated using the SR index, as used previously by Lee & DiBartolomeo [2002].

The results of the study provided evidence of energy savings as a result of the window retrofit. This was expected; since the previous windows were single glazed with tinted glass and the window retrofit was accompanied by other energy efficiency improvements, including an upgrade of the electric lighting to an occupancy-based dimmable system. As regards occupant interaction with the EC windows, the study found that the manual controls were not used very often (they were used during 14 out of 328 meetings that took place in the room during the data collection period). On some occasions, users appeared to use the switches in a way that suggested that they desired more daylight than that provided by the automatic system, *e.g.* by leaving one pane clear and the others tinted. The window blinds were never fully lowered, and their position was not

changed much during the data collection period. The authors concluded that the infrequent use of blinds indicated that the EC window provided good control of discomfort glare without the need for additional shading. However, it was also noted that a building opposite provided the benefit of blocking low angle sun to the western façade. The authors could only speculate about the motivations behind the interactions due to the absence of user feedback. In conclusion, the authors pointed to a need for further research in real buildings fitted with EC glazing that incorporates data about user acceptance.

#### **2.2.4 Research gap**

Previous research has established the energy saving potential of EC glazing, but studies involving human participants are rare, meaning that there is still a lack of understanding about the occupant experience of EC glazing. Research to date has indicated that EC glazing with a minimum transmittance of 2% might be able to provide adequate control of daylight glare without the need for blinds, and there is a suggestion that a minimum transmittance of less than 2% is necessary if the need for blinds are to be completely removed. However, this is in the context of a test room environment and the limited exposure time to which participants were subjected. There are also indications that the control mechanism may present a challenge to user acceptance, because it takes some minutes for the glazing to switch states (*e.g.* un-tinted to tinted). Due to the limited exposure time to which participants in test room studies were subjected, little is known about longitudinal effects, encompassing a range of seasons, weather conditions and subjective aspects such as changes in health, mood and alertness.

### **2.3 Scope of this study**

In order to more fully understand the capability of EC glazing to meet the visual comfort needs of human occupants, a study that includes the systematic assessment of the subjective experience of occupants over a long-term period is needed. Thus, the following requirements were identified for a new study of EC glazing:

1. It should be a field-study, *i.e.* based in a real building, preferably one that represents a typical office workplace.
2. The room(s) under study need to be continuously occupied, *i.e.* not a meeting room or transition space.
3. It should be longitudinal, over a period that encompasses a wide range of sun positions and weather conditions.
4. The occupants must be willing to provide information about their experience of the EC windows at regular intervals.
5. Data collection should include physical monitoring of the space so that objective data about luminous conditions are captured in addition to data from participants.
6. It should be possible to interrogate the EC glazing control system and to change the settings. The system should be capable of providing a data log, *e.g.* sensor readings, tint states, and control modes.

### **2.4 Research questions**

The overarching question to be addressed by this study is thus: “What is the experience of end-users of EC glazing over a long-term period, particularly with regard to visual comfort?” As a real world study, the work is exploratory in nature rather than conforming to a hypothesis-testing model. The design therefore needed to be flexible enough to adapt to the study site and its occupants, but structured enough to ensure that the data addresses the research enquiry as fully as possible.

The overarching research question was broken down into four main areas of research enquiry, as follows:

1. Visual comfort: How well did EC glazing provide visual comfort for users?
2. EC glazing colour: How important was the colour of the EC glazing tint for users?
3. Retrofit process: What can be learned from the process of retrofitting EC glazing?
4. Controls: What was the user experience of the control interface and control system?

These broad questions were each broken down into more specific questions that could be addressed by the data collected in this study; these are summarised in Table 2.2 and discussed in the paragraphs that follow.

**Table 2.2      Research questions**

1	How well did EC glazing provide visual comfort for these users?	
Visual comfort	1.1	How did EC glazing affect lighting conditions in the space?
	1.2	What were occupants' experiences of visual discomfort?
	1.3	How did occupants respond to visual discomfort?
	1.4	Can data from a mixed methods study be used to link measured lighting conditions with occupants' perceptions?
2	How important is the colour of the EC glazing tint for users?	
EC glazing colour	2.1	How did the glazing tint colour affect the view through the window and the appearance of colours in the room?
	2.2	How did the glazing tint colour affect the occupants in non-visual ways?
3	What can be learned from the process of retrofitting EC glazing?	
Retrofit process	3.1	What are the practical issues relating to the installation and commissioning?
	3.2	How did the retrofit and post-installation period affect the overall user experience?
4	What was the user experience of the controls?	
Controls	4.1	What were users' perceptions of the control interface and different control modes?
	4.2	How responsive did users find the system to manual inputs and changing external conditions?
	4.3	How should the control algorithm be optimised to suit the site and users?

### *1. Visual comfort*

This is the main focus of the study, and leads to a number of questions about how EC glazing affects lighting conditions in the space (both perceived and measured), as well as the nature of occupants' experiences of visual discomfort. The inclusion of physical measurements in addition to participant data also makes it possible to explore the relationship between measured and perceived lighting conditions.

## *2. EC glazing colour*

EC glazing takes on a visible colour when tinted. The potential significance of the glazing colour is considered in terms of how it affects the appearance of the room environment, as well as whether it affects the users directly; for example by influencing their alertness levels or mood.

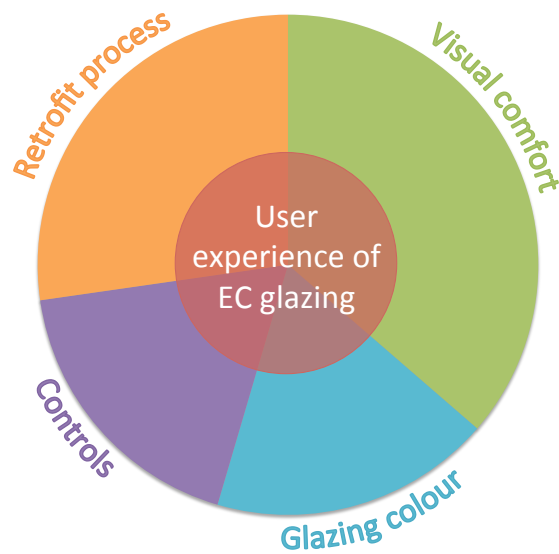
## *3. Retrofit experience*

The process of installing EC glazing provides an opportunity to understand the practical issues of implementing this technology, particularly in a retrofit installation. Thus, it is important to examine these issues for the benefit of future installations. The occupants' experience of the installation and post-installation period is also a key part of a new study, and it is valuable to consider what role this experience has on their overall impressions.

## *4. Controls*

It is important to understand how the users experienced the EC glazing controls. This is considered in terms of both the control interface as well as the perceived system performance, *i.e.* how the windows responded to both manual inputs and changing external conditions. During the post-installation period, the refinement of the control system, to optimise it for the site and users, provides a valuable opportunity to learn about the process of control system refinement for future installations.

Figure 2.3 illustrates how the overarching question is composed of research questions from the four main areas outlined above, with visual comfort representing a relatively larger share of the enquiry than other aspects.



**Figure 2.3** Composition of the research enquiry

The research questions are addressed in Part III of this thesis (Results), however due to the interrelated and overlapping nature of the questions, the chapters do not directly map to the research questions. To aid in the navigation of these chapters, Table 2.3 gives an overview of how the Results chapters address specific research questions.

**Table 2.3** How the findings chapters address specific research questions

	Research Questions										
	Visual comfort				Colour		Retrofit		Controls		
	1.1	1.2	1.3	1.4	2.1	2.2	3.1	3.2	4.1	4.2	4.3
Chapter 6											
Chapter 7											
Chapter 8											
Chapter 9											
Chapter 10											



## **2.5 Summary**

Since the 1990s, several studies of EC glazing have been carried out using computer simulations, scale models and full-sized test rooms, which have signalled the potential of EC glazing as an energy-saving fenestration material. However, few studies have included the perspective of the user, and almost all of these are based in test rooms, with only one real-world study identified in the literature. Thus, a longitudinal study in a real world setting that includes the user perspective is needed. The research gap has helped to define the scope of a new study of EC glazing, and a number of research questions have been identified, to be addressed by this new study.

## **Chapter 3**

### **The study of occupant interaction with shading**

In Chapter 2, it was seen that few previous studies of EC glazing have included human participants, and only one published study that took place in a real-world setting was identified (and this did not use data collected directly from participants). Thus, in order to understand what methods are appropriate for use in a new study of EC glazing, it is necessary to look more widely at studies of occupant interaction with shading systems in general.

In this chapter, studies that have focussed on human factors in the design of shading are examined, with a focus on the methods used to record users' experiences and interactions with shading devices. Many of the issues identified by studies of even simple shading devices, such as manual blinds, are relevant to the design of all shading systems, since at their core they seek to answer the same questions: What motivates occupants to deploy shading, what physical conditions produce visual discomfort, and how does the mode of control affect user acceptance? Some issues are more specific; for example, the effect of glazing colour in the case of fixed or dynamic tinted glazing.

First, studies that sought to quantify visual comfort are described, as this is a key component in the understanding of user interaction with and acceptance of different shading systems. This is followed by a literature review of studies of user response to shading devices, including manual and automated blinds, tinted (or coated) glazing, and EC glazing.

#### **3.1 Measures of visual discomfort**

Progress in the understanding of visual discomfort is a crucial step in the effort to improve daylighting and shading systems design. The ability to measure and predict visual discomfort can facilitate the development of more accurate models of occupant interaction with shading systems for the benefit of energy modelling, and enabling more effective control algorithms for automated shading systems to be achieved. Furthermore, visual discomfort evaluation forms an important

part of post-occupancy assessments, which can enable improvements to be made to existing buildings and to inform future designs.

### **3.1.1 High dynamic range (HDR) imaging**

The use of HDR imaging has become important in the study of visual comfort [Inanici, 2006; Beltran, 2005], following developments in camera technology and the advent of digital HDR photography. A HDR image taken using a wide-angle or fish-eye lens can be used to approximate the illuminated scene that is perceived by a human occupant. The images can be analysed to gain useful insights into why, for example, one scene is considered preferable or more visually comfortable than another. More crucially, it can be used to gain an understanding of the criteria that must be met in order for an area of the scene to be considered a glare source to an observer.

In an illuminated space, surfaces reflect the light that falls upon them, making them visible to the human eye. The amount of light reflected back depends on the properties of the surface material, primarily its colour and texture. For a human observer, each surface is perceived as having a different brightness, and for the purposes of lighting calculations, surface luminance,  $L$  ( $\text{Cd}/\text{m}^2$ ) is used as a proxy for brightness sensation. Brightness can be related to luminance using Stevens' Law:  $B \approx L^{0.31}$ , where  $B$  is the perceived brightness and  $L$  is the luminance in  $\text{Cd}/\text{m}^2$  [Bodmann, 1992]. A HDR image is a composite of a number of photographs taken at a range of different exposures, thus containing a much wider range of luminance levels than a regular photograph taken at one exposure. In this way, the HDR image contains a range of luminances that is more closely aligned to the human visual system, which can perceive an extremely wide range of brightness levels in one scene. Once calibrated and adjusted for the lens vignetting effect, as recommended by Jacobs [2007], each pixel in the HDR photograph can be assigned a particular luminance level and the image can then be analysed to produce a range of data about lighting conditions in the space. As such, the HDR image is considered a "luminance map" of the scene [Inanici, 2006]. HDR photography can be used to produce luminance maps of existing scenes, as in the case of studies using real buildings or test rooms, and can also

be produced from computer models as a design tool, for example using Radiance software.

### 3.1.2 Daylight glare metrics

As discussed in Chapter 1, glare is a subjective phenomenon, which makes it inherently difficult to measure in an objective way. As well as variables in the luminous environment, glare is subject to a variety of factors specific to the individual (*e.g.* eye health, age, gender). Glare from windows is particularly complex, since the factors involved are more numerous and less predictable compared with glare from electric lighting sources. Nonetheless, the quest continues to find a more accurate daylight glare metric because of its high potential value as a design tool.

Several efforts to develop a daylight glare metric [*e.g.* Hopkins, 1972; Einhorn, 1979; Iwata, 1991; Osterhaus, 1992; CIE, 1995; Nazzal, 2005] were limited by their bases in experiments that used artificial light sources of fixed and predictable quantities, instead of daylight from real windows. The metrics that resulted from these studies include Daylight Glare Index (DGI) [Hopkinson] and Cornell Glare Index (CGI) [Einhorn], and New Daylight Glare Index (DGI<sub>N</sub>) [Nazzal]. These were subsequently found to have limited applicability in real daylight spaces [*e.g.* Weinold & Christoffersen, 2006; Painter *et. al.*, 2009]. Osterhaus [1996] proposed the subjective rating (SR) index, based on empirical data from two experiments with a single task and fixed background luminance. Subjective glare ratings given by participants were found to correlate reasonably well with calculated values of CGI, and weakly with DGI, but the best correlations were found for vertical illuminance at the observer's eye and brightness levels derived from luminance at the eye of the observer. SR has been used in some studies of EC glazing, particularly where no human participants were involved and thus no subjective data were available [Lee & DiBartolomeo, 2002; Lee *et. al.*, 2012]. In these studies, vertical illuminance on the inner surface of the window was used instead of vertical illuminance at the eye of the observer to estimate the potential for glare.

### *HDR-based daylight glare metrics*

Several studies concerned with visual comfort in daylit rooms have used metrics derived from HDR images and empirical data from occupants to test the validity of existing daylight glare metrics, and to develop new metrics [e.g. Weinold & Christoffersen, 2006; Bellia *et. al.*, 2009; Fan *et. al.*, 2009; Van Den Wymelenberg *et. al.*, 2010; Hirning *et. al.*, 2013]. As a result of this research, a number of new daylight glare metrics have been proposed, the most notable of which is Daylight Glare Probability (DGP), presented in 2006 by Weinold & Christoffersen. However, attempts to validate DGP in other settings have yielded mixed results [e.g. Painter *et. al.*, 2009; Van Den Wymelenberg *et. al.*, 2010; Hirning *et. al.*, 2014], and suggest that it has limited applicability to room and window geometries that deviate from those used in the study on which it is based (e.g. relatively large windows, with seating positions near the window wall).

Several studies [e.g. Painter *et. al.*, 2009; Van Den Wymelenberg *et. al.*, 2010; Hirning *et. al.*, 2014] have found that field-of-view based luminance parameters correlated more strongly with subjective glare sensation than other glare metrics. These include mean luminance of the scene, mean task luminance, background luminance (to the task), maximum luminance of the glare source, standard deviation of scene luminance and logarithm of the average scene luminance. These findings echo the previously mentioned findings of Osterhaus [1996] and Velds [2002], whose results indicated that vertical illuminance and luminance at the eye of the observer (Osterhaus) and near to the façade (Velds) correlated relatively well to the glare sensation experienced by participants.

Further work has also considered how occupant behaviour might affect the prediction of daylight glare using HDR-based metrics. For example, Jakubiec & Reinhart [2012], showed how changing view position could significantly reduce the glare experienced by occupants in daylit spaces; implying that glare metrics based on the assumption of a fixed viewing position might tend to overestimate its severity.

### 3.1.3 Subjective evaluation of visual discomfort

The assessment of visual comfort is an important element of post-occupancy evaluations (POEs) and indoor environmental quality (IEQ) assessments, which facilitate the appraisal of the design and energy performance of existing buildings. Whilst direct measures of visual discomfort are available, such as ocular muscle electrodes [Lin *et. al.*, 2015] and measurement of eye openness [Yamin Garreton *et. al.*, 2015], these are not easily applied in real world settings, and are usually restricted to lab-based studies. In occupied buildings, self-reported data are typically used, collected via questionnaires or interviews, with simultaneous measurements of environmental variables (*e.g.* illuminance levels).

From the point of view of lighting, the assessment of visual comfort using empirical data is of central importance, as it allows the evaluation of perceived lighting quality, and thus the effectiveness of daylighting and shading strategies. This is particularly beneficial where innovative shading solutions with automated elements are used [*e.g.* Lee *et. al.*, 2013; Konis, 2013; Meerbeek, 2014], as it can inform the development of more effective models of user interaction with automated lighting and shading systems. Furthermore, there is evidence of a strong association between positive appraisals of lighting quality (and visual comfort) and overall satisfaction with the workplace environment and increased job satisfaction [Boyce *et. al.*, 2006; Veitch *et. al.*, 2011].

Hygge & Lofberg [1999] developed a POE questionnaire for daylit offices and used it in five case studies. The results indicated that lighting and temperature are the two most important aspects for occupants. Their questionnaire contained a total of 37 items, and included general questions about the occupants (*e.g.* age, gender, eye health, occupation), as well as more specific questions about their preferences and satisfaction with conditions in their offices, particularly pertaining to lighting, daylighting and windows. These questions covered topics such as satisfaction with overall light level, quantity of daylight and frequency, source and severity of visual discomfort (glare and reflections from screens and other surfaces). The length of this questionnaire makes it less suited to situations where questionnaire completion time needs to be minimised. However, as it

contains both general and specific elements, it can be adapted for use in a variety of situations.

Subsequent studies of user experience of automated shading and daylighting systems, such as Vine *et. al.* [1998] and Clear *et. al.* [2006], used questionnaires containing many of these elements, and sought to collect general background information as well as specific information about participants' experiences of the shading system under study (automated blinds in the case of Vine *et. al.* and EC glazing in the case of Clear *et. al.*).

Aries *et. al.* [2010] conducted POEs of over 300 workers in 10 office buildings in the Netherlands, with the aim of developing a model of the physiological and psychological mechanisms that underlie the comfort of building occupants. Their survey contained items related to the general characteristics of the individual (background) as well as questions about the occupants' experience of their office. Background questions covered aspects such as sleep quality, propensity to minor illnesses (such as colds and headaches), as well as sensitivity to visual discomfort. Participants were asked to indicate how often direct sun in the office caused problems, such as glare and overheating, and about the view through their windows. The results indicated that attractively rated window views reduced discomfort, but that being close to a window can result in thermal and glare problems. The results also suggested that reduced discomfort at work might improve sleep quality.

A survey of 83 office workers across nine daylit buildings described by Osterhaus [2005] included items related to participants' sensitivity to glare and lighting preferences, as well as how often they experienced glare and how they rated lighting quality in their current office. It also asked participants to rate level of daylight in the office (ranging from too dark to too bright) and included a simple question about the participant's emotional state (on a seven-point scale ranging from very poor to excellent).

Laurentin *et. al.*'s [2000] work used questionnaires to study the relationship between thermal conditions and visual comfort. Their survey included an item asking participants to rate the pleasantness of their office at the time of response, with respect to lighting and thermal conditions. Whilst they did not

find a link between thermal conditions and visual comfort appraisal, their results did suggest a preference for lower illuminance levels under electric lighting than under daylight.

Vischer & Fischer [2005] used a detailed post-occupancy questionnaire to investigate how instruments such as POEs can be used to explore the relationship between user comfort in the workplace and job satisfaction. They argued that surveys need to take a more diagnostic approach, evaluating not just occupants' current levels of comfort and satisfaction with their offices, but also social and psychological effects, such as privacy for conversations, background noise and furniture layout. Their questionnaire covered a wide range of environmental variables, including temperature, noise level, air freshness, storage provision and furniture layout. A limited number of items addressed lighting and there was one question about the perceived adequacy of the view through windows.

It can be seen from the literature that the subjective assessment of visual comfort in workplaces has been largely based on surveys or questionnaires. These include a diverse range of items, covering a variety of room environmental parameters; not just occupants' experiences of lighting conditions, but also their perception of other aspects of their work environment that might affect their perception or tolerance of lighting conditions, such as temperature or noise levels. When assessing occupants' perceptions of lighting conditions, several studies have used a similar approach, and have included questions about the lighting preferences and sensitivities of the individual, as well as light levels and the occurrence of glare and screen reflections in their current workplace. Further details about the questions used in previous studies are discussed in Chapter 5, where the self-reported data collection used in this study is described.



### 3.2 Studies of occupant interaction with shading

As discussed in Chapter 1, several studies of occupant interaction with manual blinds have found that occupants often use blinds in a way that is sub-optimal from the point of view of both energy use and occupant well-being. Automated shading can resolve this issue, but motorised components can add cost and complexity to the façade, and the design of effective control algorithms for automated shading can be particularly challenging.

A number of studies of occupant interaction with shading systems have been carried out in an effort to understand the factors that contribute to blind opening or closing behaviour (see Table 3.1). These studies have been largely driven by the need for more realistic models of occupant behaviour to improve the accuracy of building energy modelling. This is particularly important given the widespread use of computer simulation as a building design and energy compliance tool, since assumptions about shading usage patterns in computer models can have a significant impact on predicted energy consumption [Da Silva *et. al.*, 2012].

For automated shading systems, the potential rewards of research include the development of more effective control algorithms to better anticipate users' needs. Automatic control systems that are perceived by occupants to regularly contradict their wishes can lead to higher energy consumption because of misuse; uncomfortable occupants will resort to whatever measures they can in order to achieve comfortable conditions, negating the original design intent of the system [O'Brien, 2013]. As mentioned in Chapter 1, the provision of manual in addition to automatic control is crucial, but this will not be sufficient to ensure user acceptance if the automatic control algorithm appears to conflict with the needs of occupants.

Table 3.1 summarises a literature review of 20 studies concerned with occupant interaction with shading devices, including manually controlled, automated shading and EC glazing. Six of the studies were based in test rooms, whilst the others were post-occupancy or field studies that had real-world settings. An overview of the methods used in these studies is provided. In the majority of studies, the use of electric lighting controls was monitored in addition to shading

usage, however, details of how electric lighting usage data were collected have not been included in this review.

It can be seen that, with the exception of Rubin [1978] and Rea [1984], who collected only observed data about blind positions, these studies used a mixture of data from different sources to gain an understanding of occupants' visual comfort and use of shading. In most cases, shading usage was monitored along with the collection of self-reported data from occupants and physical measurements, such as internal light level, temperature and weather conditions (though only the methods used to collect measured data about interior lighting conditions have been included in this summary).

In almost all of the studies reviewed, shading usage was recorded systematically by the monitoring of shade positions (or, in the case of EC glazing studies, window tint state). In many cases, photographs or video footage of the façade was used. In some studies, such as Reinhart & Voss [2003], Mahdavi *et. al.* [2008], Da Silva *et. al.* [2013] and Meerbeek *et. al.* [2014], this process was automated so that a high density of observation could be achieved. In some studies, the analysis of the images was also automated. However, this proved difficult where Venetian-type blinds were used, and thus slat positions, as well as level above the sill, needed to be recorded (*e.g.* Meerbeek *et. al.*).

The majority of these studies collected self-report data from participants about their visual comfort, satisfaction with lighting and shading, and in some cases, shade usage. All but two of these used questionnaires; Escuyer & Fontoynt [2001] and Meerbeek *et. al.* used a semi-structured interview, with Meerbeek *et. al.* also using diaries to collect daily information about occupants' comfort and shade usage.

In six of the studies [Vine *et. al.*, 1998; Clear *et. al.*, 2006; Zinzi, 2006; Inkarojrit, 2008; Konis, 2013; Bakker *et. al.* 2014], data from all three streams (self-report, observed and measured) were collected simultaneously or at around the same time, in an effort to investigate possible links between measured conditions in the space and occupant-based data (self reported or observed shade use behaviour). Three studies [Inkarojrit, 2008; Da Silva *et. al.*, 2013 and Konis, 2013] used HDR images to record interior luminous conditions, and were thus

able to explore the relationship between luminance-based metrics of visual comfort and perceived conditions.

The number of participants involved in the data collection varied greatly, from eight in the case of Sutter *et. al.* [2006] to 794 in the case of Inoue *et. al.* [1988]. However, it is noted that in studies with large sample sizes (*e.g.* Inoue *et. al.* and Lee *et. al.*, 2013), the data were almost exclusively survey-based and only collected once, *i.e.* a one-off survey was issued to all the occupants of an entire building or buildings. In real-world studies that had relatively low numbers of participants, such as Sutter *et. al.* and Da Silva *et. al.*, data were collected from participants on a repeated-measures basis, and efforts were made to collect data at as high a frequency as possible (every 15 minutes for Sutter *et. al.* and every 20 minutes for Da Silva *et. al.*).

In many of the studies that had real-world study settings, the data collection was shaped by the constraints imposed by the site and the need to respect the privacy and workload of the participants. For example, Meerbeek *et. al.* used a low-resolution camera to capture façade photographs to protect the identity of the occupants inside, and as a result were not able to obtain a detailed record of the blind slat positions. Da Silva *et. al.*'s participants failed to complete their questionnaires at all, resulting in no self-reported data. This highlights the particular challenges of collecting data about occupants' behaviour and experiences in a real world environment.

**Table 3.1 Overview of studies of occupant interaction with shading devices**

Study	Setting	Shading type	Number of participants	Data collection methods		
				Self-reported data	Observed shading usage	Physical measurement of interior lighting conditions
Rubin <i>et. al.</i> 1978	Real world	Manual blinds	None	-	Façade photographs	-
Rea 1984	Real world	Manual blinds	None	-	Façade photographs	-
Inoue <i>et. al.</i> 1988	Real world	Manual blinds	794	Questionnaires	Façade photographs	-
Vine <i>et. al.</i> 1998	Test room	Automated blinds	14	Questionnaires	Blind positions monitored	Workplane illuminance
Escuyer & Fontoynt 2001	Real world	Manual blinds	41	Semi-structured interviews	None (blind usage was included in self-report data)	Workplane illuminance
Foster & Oreszczyn 2001	Real world	Manual blinds	None	-	Façade video footage	-
Reinhart & Voss 2003	Real world	Automated blinds	None	-	Façade video footage	Workplane illuminance supplemented by simulations
Clear <i>et. al.</i> 2006	Test room	EC + manual blinds	43	Questionnaires	Blind positions and EC window controls monitored	Workplane illuminance
Sutter <i>et. al.</i> 2006	Real world	Manual blinds (some remotely controlled)	8	Questionnaires	Blind positions monitored	VDU screen illuminance
Zinzi 2006	Test room	EC + manual blinds	30	Questionnaires	Blind positions and EC window controls monitored	Workplane illuminance
Mahdavi <i>et. al.</i> 2008	Real world	Manual blinds	None	-	Façade photographs	Workplane illuminance
Inkarojrit 2008	Real world	Manual blinds	113 (questionnaires) 25 (field study)	Questionnaires	Blind positions monitored	Visual field luminance using HDR
Lee <i>et. al.</i> 2012	Real world	EC + manual blinds	None	-	Blind positions visually observed, EC window controls monitored	Workplane and vertical window illuminance

Study	Setting	Shading type	Number of participants	Data collection methods		
				Self-reported data	Observed shading usage	Physical measurement of interior lighting conditions
Lee <i>et al.</i> 2013	Real world	Automated blinds	665 (questionnaires)	Questionnaires	Blind positions and manual overrides monitored	Workplane illuminance (electric lighting only)
Da Silva <i>et al.</i> 2013	Real world	Manual blinds	8 (blind use)	Questionnaires (but no data collected due to lack of response)	Blind positions determined from HDR photographs	Workplane illuminance and visual field luminance using HDR
Konis 2013	Real world	Manual blinds	44	Questionnaires	Blind positions determined from HDR photographs	Workplane illuminance and visual field luminance using HDR
Bakker <i>et al.</i> 2014	Test room	Automated blinds	26	Questionnaires	Blind positions monitored	Horizontal and vertical workplane illuminance
Meerbeek <i>et al.</i> 2014	Real world	Automated exterior blinds and manual interior blinds	17	Diaries and semi-structured interviews	Exterior blinds only using façade photographs	-
Li <i>et al.</i> 2015	Test room	EC and manual blinds	84	Questionnaires	<i>Unclear</i>	Illuminance (further details not available)
Zarkadis & Morel 2015	Test room	EC and manual blinds	9	Questionnaires	EC window state and blind use monitored	Workplane illuminance

It can be seen that a considerable number of studies of occupant interaction with shading have been carried out, with the aim of improving our understanding of the factors influencing both visual comfort and occupant behaviour around shading systems. The studies have used a variety of methods, and many have taken a mixed methods approach, incorporating the collection of physical and occupant-based data. In most cases, the collection of data from occupants has included both self-reported and observed data. This approach is valuable because it can produce information about the occupants' experience from more than one perspective and overcome some of the limitations of these methods when used alone. For example, the reliability of self-reported data is subject to a number of issues, such as participants misreporting their behaviour or perceptions (consciously or otherwise) [Yan *et. al.*, 2015], which can be partly addressed by using observational methods to support the data obtained from self-report channels. On the other hand, observed data alone cannot usually explain the motivations or contextual factors influencing occupant behaviour, and thus are complemented by first-hand information from occupants about their experiences. Hence, a multi-stranded data collection incorporating physical measurements, self-reported and observed data is a proven approach in the study of occupant response to shading systems.

### **3.3 Studies of occupant response to tinted glazing**

As mentioned in Chapter 1, studies of tinted glazing (and the methods used therein) are relevant when considering a study of EC glazing. Though, unlike EC glazing, these materials have fixed optical properties, EC glazing acquires similar characteristics in its reduced transmittance states, and it is the effects of the glazing in this state that is of particular interest. A small number of studies have investigated the effects of tinted glazing materials of different colours on human observers [*e.g.* Cuttle, 1979; Arsenault *et. al.*, 2012; Hraska *et. al.*, 2014]. Others have looked at the effects of glazing materials with a range of selective treatments for solar heat gain control, such as low-emissivity coatings [*e.g.* Bulow-Hube, 1995; Dubois, 2007]. Although these materials do not necessarily have a visible coloured tint, they filter the spectrum of light entering through

them, and thus can alter the appearance of objects in the interior, as well as having other non-visual effects.

Cuttle [1979] used a scale model of an office with a window in one wall and a liquid-based filter that could simulate a range of different glazing colours. 18 participants sat with their upper body immersed in the model and were allowed to adjust the depth of tint of the simulated window until it was just too bright or just too dark. Tests were conducted on three different tint colours: grey, bronze and blue. After each test, participants were interviewed (though the interview questions used were not made explicit in Cuttle's paper). Thus, this methodology combines elements of self-report data collection with observations of occupant-selected preferences.

Arsenault *et. al.* [2012] also used a scale model of an office in which participants could immerse their upper bodies. Their study sought to evaluate the non-visual effects of three different glazing types (blue tint, bronze tint, and neutral). Self reported data were collected from 36 participants using oral and written questionnaires. In addition to the collection of subjective data, the exterior vertical illuminance and horizontal desk illuminance were measured. For the written questionnaire, five-point bi-polar Likert scales were used to assess participants' perceptions of lighting conditions, appearance of the view through the window, the appearance of objects in the room, and the appearance of colours in a picture within the room. The written questionnaire was detailed, with several separate items (rating scales) associated with each aspect. The texture and appearance of objects was assessed separately from the colour of daylight, using a number of scales including "natural – artificial" and, in the case of the appearance of colours in a picture, "lively – dull". Before and after immersion in the model for each glazing evaluation, participants were asked to rate their alertness using the Karolinska Sleepiness Scale (KSS) [Kaida *et. al.*, 2006]. The KSS item uses a nine-point scale on which participants rate their level of alertness or sleepiness, from "extremely alert" to "extremely sleepy, fighting sleep". This tool has also been used in studies of the non-visual effects of lighting spectrum and quantity, such as Smolders *et. al.* [2012].

The participants in Hraska *et. al.*'s [2014] study were dementia patients; thus, direct measures were used rather than self-report data collection. In this study, participants wore a Daysimeter (a device worn on the wrist that monitors light exposure), and urine samples were taken so that levels of biological markers indicating melatonin secretion could be determined.

Bulow-Hube [1995] compared the effects of a clear triple-glazed window and a quadruple-glazed window with two low-e coatings using two (full-sized) test rooms. A questionnaire was used to collect self-reported data from 95 participants, which used seven-point bi-polar scales. The questionnaire included items relating to the perception of lighting conditions, glare, the appearance of colours in a poster on the wall and perception of the weather outside (by looking through the window). In addition to the questionnaire data, the illuminance was measured in the centre of the room at workplane height before and after each test.

Dubois *et. al.* [2007] compared subjective evaluations of six different glazing types with different types of low-e coatings. They used scale models, and collected data from 18 participants using a questionnaire based on the one used by Bulow-Hube. In addition to the subjective data, a number of measurements were made during the tests, including interior horizontal illuminance, exterior vertical illuminance and daylight spectra within the model.

It is noted that Cuttle, Arsenault *et. al.* and Dubois *et. al.* all used scale models. Whilst the use of scale models for lighting research is considered to be valid [Lau, 1972], its use in the evaluation of the non-visual effects of daylight with different glazing colours has one significant limitation: participants can only be exposed to conditions for very limited periods, in a somewhat unnatural setting. Nonetheless, the use of scale models allowed small glazing samples to be used and easily changed between test sessions, as well as making it easier to carry out side-by-side comparisons of test and references cases. In a full-sized installation, this kind of flexibility is not usually feasible.



### **3.4 Summary**

The methods used in a number of studies of visual comfort, occupant interaction with shading devices and occupant responses to different types of tinted and coated glazing have been reviewed. The wide range of approaches and techniques used to gather data about occupants' subjective experiences and behaviour (in the case of shading usage) demonstrates that a mixed methods approach is needed to study the user experience of EC glazing in a real-world setting. In a literature review of 20 studies of occupant interaction with shading devices, it was seen that a combination of methods are needed to capture information about users' perceptions as well as direct observations of shading use, in addition to physical measurements of lighting conditions. The simultaneous collection of data from three main strands (self-reported, observed and measured) allows the exploration of relationships between subjective and measured data. In three of the studies reviewed, the interior luminous conditions were captured using HDR photographs, giving the added opportunity to investigate links between self-reported visual discomfort and measured luminance-based variables.

The research questions and methodological approach have now been defined. In the next chapter, the study setting will be described, leading to the detailed design of the data collection programme.

## **Part II      Methodology**

This part of the thesis is concerned with the study setting and the methods used to collect data within it. Chapter 4 describes the study site and the electrochromic window retrofit that formed the basis of this study. As a real world setting, the site and its occupants impose a number of constraints upon the data collection methodology, and these are highlighted. In Chapter 5, the methods used to collect data are described in detail, including the sampling interval and data collection period related to each aspect.

## Chapter 4

### Study setting

#### 4.1 Case study site

Two office rooms in a De Montfort University (DMU) campus building, identified as room A and room B, were chosen as a site for an EC glazing retrofit and subsequent study, with the agreement of the university estates department. The rooms were occupied by a total of eight employees who provided administrative support to academic staff. There were several aspects of this site that made it particularly suitable:

- It had large southeast-facing windows, so the glazing typically experienced high levels of solar irradiation throughout the year, and regular solar penetration during the mornings (see Figure 4.1). This was evidenced by the fact that blinds in these offices were often partly or fully closed.
- The existing double-glazed units were in poor condition and in need of replacement.
- It was a continuously occupied space (*i.e.* not a transitional space or meeting room), which made it possible for the experiences of occupants to be monitored over a long term period.
- The staff within the rooms carried out routine office work tasks, such as computer work, printing, scanning, photocopying and answering phones. This enabled EC glazing to be studied in a typical office setting.
- As it was part of a different faculty to that of the research team, the staff had no professional interest in the subject that could introduce bias in this regard.



**Figure 4.1**      **Satellite views of the site showing façade orientation (left) and the sunpath (right)**

The offices had been converted from the building's previous industrial use in the Victorian era. As a result, they contained some idiosyncratic features that would probably not be found in a purpose-built office building. As shown in Figure 4.2, the two offices spanned three windows, so that each had one and a half of the original windows. In addition, a false ceiling cut across the top of the most of the windows. Blanking panels and ventilation grilles were placed in the cut-off portions instead of glazing panes.



**Figure 4.2 Idiosyncratic features of the Victorian conversion**

**Left:** The original windows, such as the one visible in the lower part of the photograph, had small glazing bars and panes that extended to the full height of the window heads.

**Right, top:** The two rooms shared three windows between them, resulting in the middle window being split by a partition.

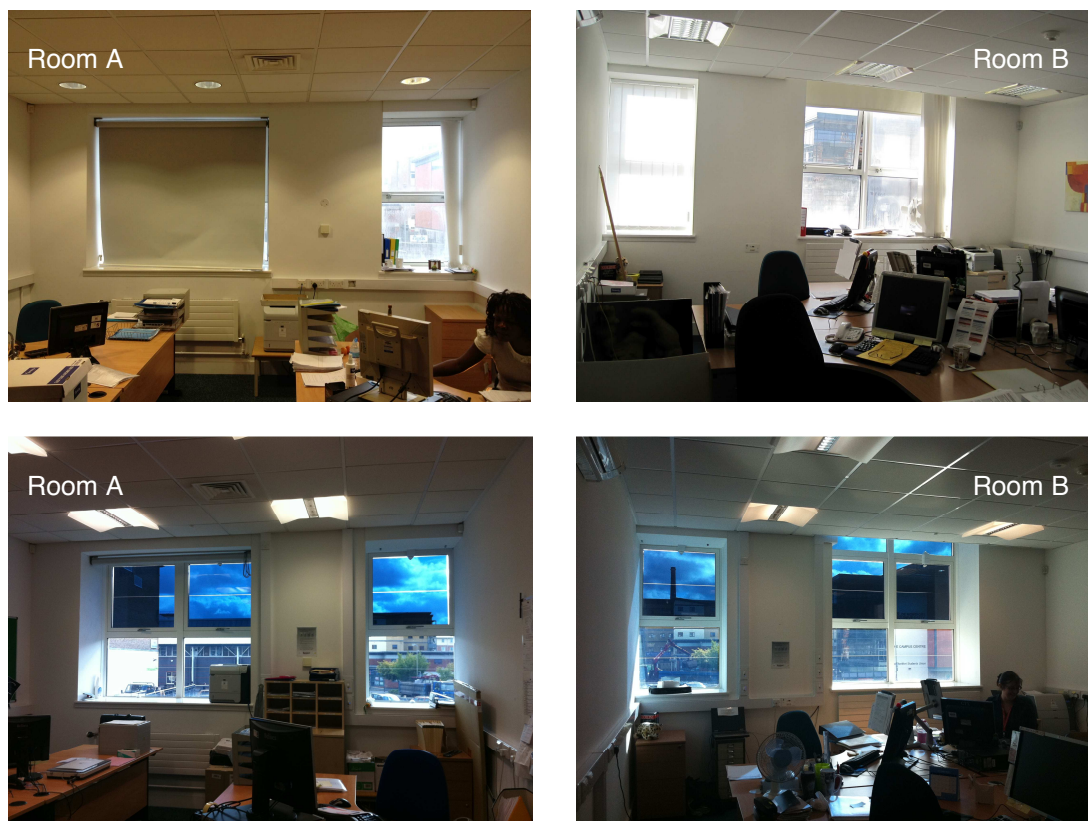
**Right, bottom:** The false ceiling cut off the top portion of most of the windows.

As such, these offices are considered to be representative of many existing UK offices in several key respects, *e.g.* their being occupied by more than one person and situated within an older building that has been converted for its current use. As a result, the findings of the study are more widely applicable to retrofit applications of EC glazing in existing building stock, which may not have been the case had the study been carried out in a new-build office fitted with EC glazing.

## 4.2 Electrochromic windows

### 4.2.1 General features and appearance

The EC windows were installed between the 28th and 30th August 2012, and were the first EC windows to be installed in a non-residential building in the UK. The windows were manufactured by SAGE Electrochromics Inc. and were made to aesthetically match the windows in the rest of the façade as much as possible, with similar white uPVC frames and opening sections. Figure 4.3 shows the interior of the offices before and after the retrofit. In the “after” photographs, the upper window panes are tinted, and it can be seen that the glass takes on a blue colour when tinted. From the exterior, the only obvious aesthetic difference is the disparity in glass transmittance, and resulting colour differences in the glazing, as shown in Figure 4.4.



**Figure 4.3** The study rooms before (above) and after (below) the window retrofit.

Note that in the “after” pictures, only the top row of panes was tinted at the time when the photo was taken; the lower panes can also be tinted.





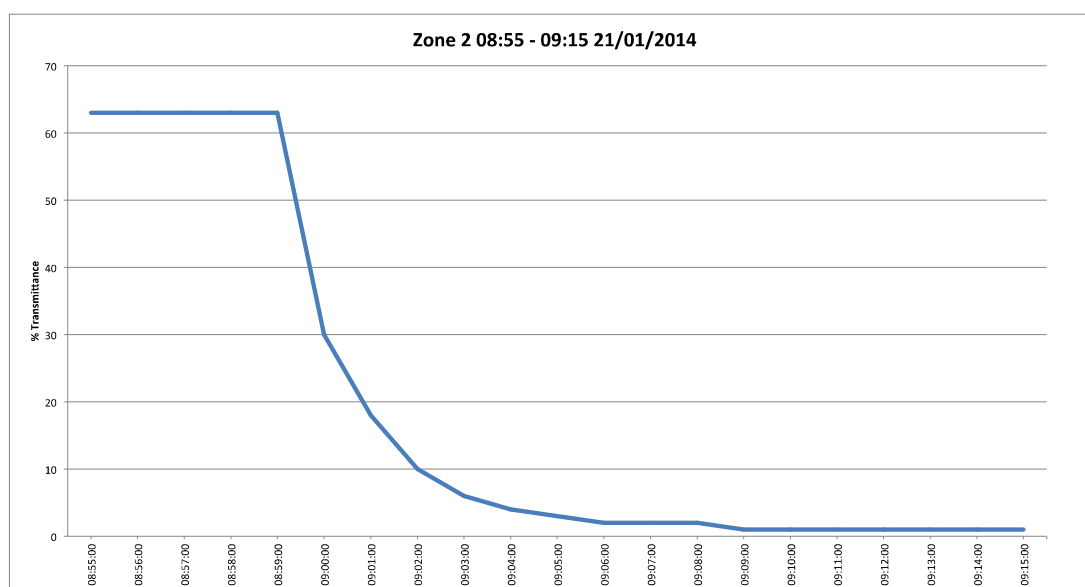
**Figure 4.4** External façade after the window retrofit, with EC windows highlighted

### *Specification*

The new windows consist of double-glazed units of 6mm tempered glass and 12.7mm argon-filled cavity, with an electrochromic coating on the inside surface of the outer pane. The units are sealed to achieve a high level of insulation using a dual system of silicone and polyisobutylene (PIB), to achieve a U-value of 1.45 W/m<sup>2</sup> K. The electrochromic coating comprises a five-layer ultra-thin coating that allows the visible transmittance of the glazing to change when subject to a small applied voltage. The visible transmittance of the glass is 62% in its least tinted (bleached) state and 2% in its fully tinted state. Between these two states, there are two intermediate tint settings, with visible transmittances of 20% and 6%. There is a narrow non-tinting area around the perimeter of the glazed units where the electrochromic coating does not extend to the edge. The glazing panes have a thin 3mm wide conductor (or bus bar) that runs horizontally through the centre. This was a requirement at the time due to the area of electrochromic coating in each pane, however, in the latest available product, larger areas of EC glazing can be tinted without the need for intermediate bus bars.

### *Transition time*

The glazing can take up to 10 minutes to complete a change in transmittance state. The transition time is increased at lower ambient temperatures and for larger areas of glass. The speed of transition is limited by the speed of diffusion of lithium ions into the electrochromic layers. Figure 4.5 shows the speed of transition from un-tinted to fully tinted on a particularly cold day in January 2014. It can be seen that the glass took almost 10 minutes after the manual switch was pressed to reach the target transmittance of 2%.

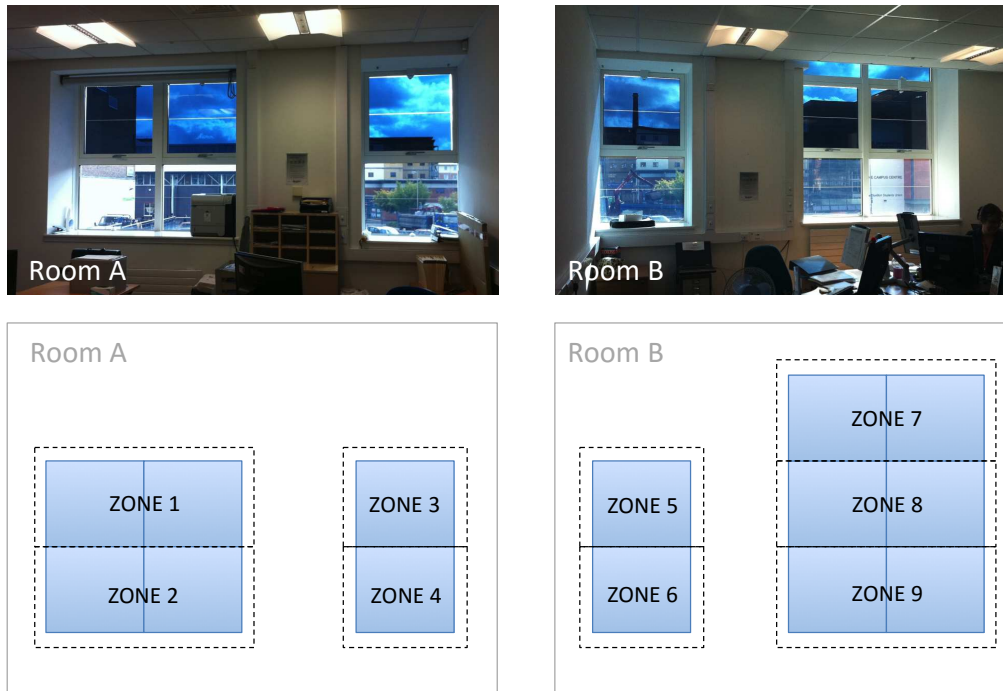


**Figure 4.5** Change in transmittance on 21st January 2014. External air temperature was 2.1 °C at 09:31.

### **4.2.2 Control system**

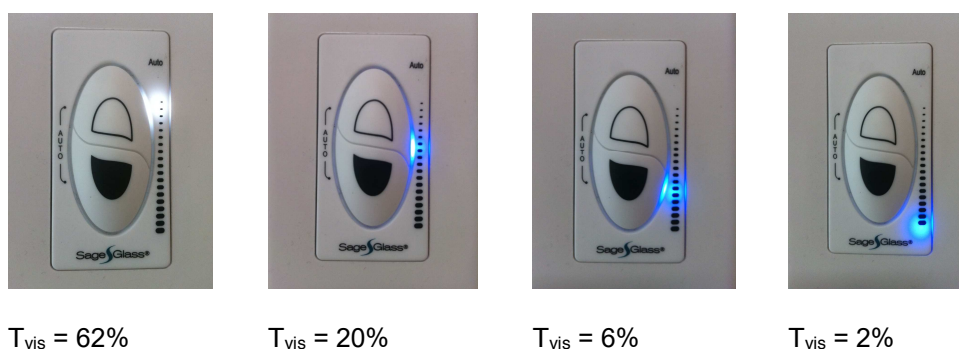
In order to give maximum flexibility of control, the windows were split into several control zones, as shown in Figure 4.6. As explained earlier, some of the windows are partially cut off by the false ceiling, which effectively means that one of the rooms (A) has one large four-pane window and one small two-pane window, whilst the other room (B) has one large six-pane window and one small two-pane window. The glazing tint of all zones is adjusted automatically by the control system (auto mode) and can be overridden by occupants using wall switches located next to the windows (manual mode).





**Figure 4.6 Window control zones**

There is one wall switch per zone, each with an indicator light that shows the tint level of the associated zone. The indicator light moves up and down in response to a cue from the automatic control system, as well as if pushed by an occupant. Figure 4.7 shows the appearance of the wall switches in different tint states, as denoted by the value of the visible transmittance,  $T_{vis}$ .



**Figure 4.7 Window wall switches**

### *Manual mode*

If a user presses a wall switch, the system responds to this command and overrides auto or glare mode by entering manual mode. The system settings determined by the wall switch command remain for a period of two hours.

### *Auto mode*

In auto mode, the control system takes its input from an illuminance sensor mounted on the external façade near the windows. The upper and lower threshold values of each zone could be set independently of each other. Upon installation, the system used the default settings, which were an upper threshold of 12 klux and a lower threshold of 3 klux for all zones. This meant that if the sensor reading exceeded 12 klux, the transmittance of that zone was decreased to the next lowest available level, and if a sensor reading fell below 3 klux, the transmittance of that zone was increased to the next highest available level. An in-built delay or 'dead-band' of two minutes is included to avoid control system hysteresis during periods of varying illuminance, such as when there are fast-moving clouds obscuring the sun for brief periods. The thresholds were later adjusted to suit the needs of the site and occupants (see Chapter 6).

### *Glare mode*

Glare mode is an automatic control mode that tints the glazing to its lowest transmittance state (2%) under bright, sunny conditions. It is triggered if two conditions are met: (a) The sun's position is such that direct sun on the windows is possible, and (b) the illuminance on the façade sensor exceeds some predetermined level. The intention of this control mode is to enable the control system to react in a more pre-emptive manner than in auto mode, thus overcoming some of the disadvantage of transition time. Glare mode was not included in the system initially, but was introduced later, in January 2013 (see Chapter 6).

Throughout the study, the control system settings were accessible by the research team, so that settings could be adjusted and recorded (see Chapter 5). This, combined with the flexibility afforded by dividing the windows into several individually controllable zones, were features that were included to facilitate the study of the EC windows, but which may not have existed in a regular EC window retrofit (*i.e.* not part of a research study). These aspects made it possible to apply different automatic control settings to each zone and to monitor the effect of changes to control system settings on individual zones.

### **4.3 Window blinds**

As discussed in Chapter 1, one of the main advantages of EC glazing is its ability to provide shading without the need for manually controlled devices, such as window blinds, which are often left in a lowered position, obscuring the view out and reducing occupants' exposure to daylight. Nonetheless, given that the performance and effectiveness of EC windows in this setting was as yet unknown, it was decided that window blinds should still be available to occupants after the EC window retrofit.

An important principle of the study was that it should not unduly interfere with the ability of occupants to carry out their work tasks. Furthermore, the need to preserve the health and safety of occupants was a key determinant of the design study process. Indeed, these values were central to gaining consent from occupants to participate in the study. If blinds were not provided, and the windows did not function properly or did not provide adequate control of glare for occupants, their ability to carry out their work tasks could be compromised.

Before the EC window retrofit, the large windows were equipped with both blackout roller blinds and vertical slatted blinds. Considering the complexity of monitoring blind use with the existing arrangement, it was decided to keep this aspect as simple as possible and provide roller blinds only on all windows. After the window installation, the existing roller blinds were reinstated on the large windows, and similar blackout roller blinds were installed on the smaller windows a few months later, in February 2013.

#### 4.4 Lighting upgrade

At the same time as the window replacement, the electric lighting system in both rooms was upgraded. The main purpose of this was to install a daylight-linked lighting control system, so that the expected increase in useable daylight in the room could be used to offset electric lighting energy consumption. The existing lighting was manually switched and was not dimmable, so lights could remain on, and at full output, even if the light provided by the windows was sufficient. Furthermore, the lighting in room A was not appropriate to its function as an office, as a result of that room having been originally fitted out as a meeting room but subsequently used as an office. The light fittings in room A consisted of recessed circular downlights, and the light level provided did not meet recommended levels for office tasks. The estates department agreed that, since the occupants of these offices were being temporarily relocated for the window replacement, it was a good opportunity to upgrade the lighting to address both the energy savings issue and the problems with the lighting in room A. The light fittings before and after the window retrofit can be seen in Figure 4.8.

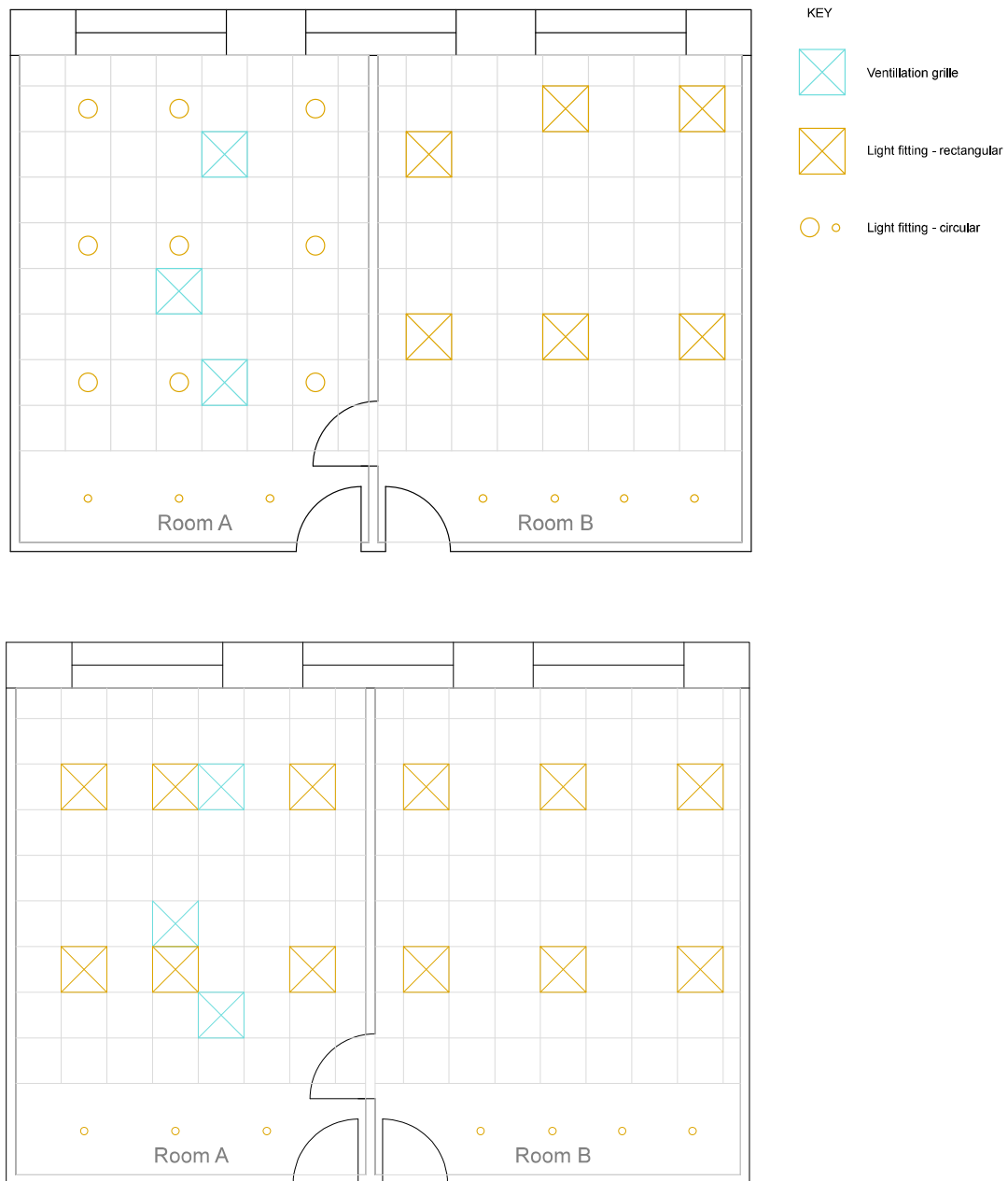


**Figure 4.8** The lighting before the window retrofit.

**Left:** The recessed circular downlighters in room A were a legacy of the room's previous use as a conference room and was not suitable for an office.

**Right:** The lighting in room B consisted of square recessed fluorescent office luminaires.

Figure 4.9 shows a plan of the lighting layout before and after the lighting upgrade and window retrofit.



**Figure 4.9** Lighting layout in room A and B before (above) and after (below) the lighting upgrade

The new light fittings were Thorn “Elevation” recessed rectangular luminaires, fitted with digitally addressable (DALI) and electronically dimmable fluorescent lamps. The new fittings were an updated version of the previously installed fittings in room B. They were similar in appearance (size and shape), light output and distribution and, as such, were appropriate as a direct replacement. Lighting

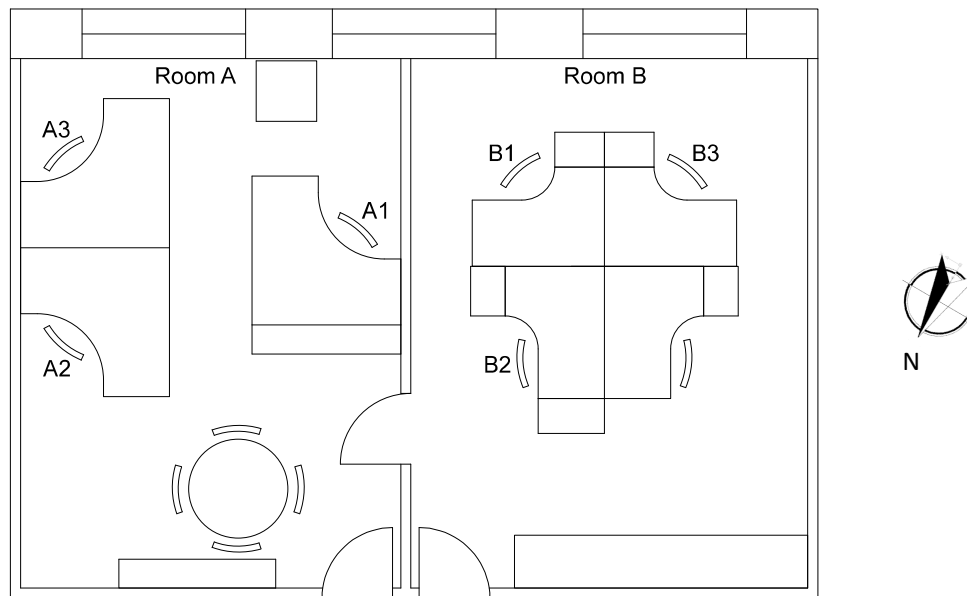
calculations were carried out to ensure that the new lighting would provide an average of 500 lux at desk height.

A Lutron “Grafik Eye” wireless DALI lighting control system was also installed. The control system included a ceiling-mounted photosensor, automatically dimming the output of the light fittings if the illuminance exceeded a predetermined level. Each row of three light fittings (running parallel to the window wall) could be controlled individually. The lights could also be controlled manually, using a control panel mounted adjacent to the existing light switches. The manual control panel allowed rows of lights to be dimmed and the programming of pre-set lighting “scenes”. The system also incorporated absence detection via a ceiling-mounted occupancy sensor, so that lights were switched off if no occupancy was sensed.

#### **4.5 Study participants**

The two offices were occupied by a total of eight employees. They spent the majority of their work time seated at their desks, carrying out computer- and paper-based tasks, using the phone and dealing with requests from people visiting their office. This allows the effects of EC glazing to be studied in a continuously occupied office setting in which “typical” office work tasks are being undertaken.

There were three desks in room A, and four in room B. Two of the employees based in room A worked part-time, sharing the same desk, so that there were a total of three employees working in that room at any one time. In room B, all four employees worked full-time. The plan layout of the offices is shown in Figure 4.10. In an effort to minimise disruption to staff, the existing desk layout was preserved.



**Figure 4.10** Layout of the study rooms

### 4.5.1 Participant recruitment

Once the study site was agreed, researchers approached the occupants of the two offices to explain the proposed study. The university estates department had already informed them that the windows in their rooms were going to be replaced with an innovative type of window, which researchers from another faculty would like to take the opportunity to study. It was explained to them that, with their consent, the study would include the collection of data directly from them about their experience of the new windows.

In April 2012, an information sheet (see Appendix II) describing EC windows, the objectives of the study and the nature of their potential involvement was given in hard copy to each occupant. They were invited to read through the information in their own time and consider becoming a study participant, thereby agreeing to provide information about their experiences of the new windows. One occupant in room A (A1) and three occupants in room B (B1, B2 & B3) said they would be willing to participate in the study. Participants A2 and A3 were not part of the main data collection, but did provide ad-hoc feedback and were included in the final set of interviews (see Chapter 7). The seating positions of the participants are indicated in Figure 4.10.

The occupants who did not wish to participate fully indicated that whilst they were happy for the study to proceed, they did not feel able to commit to participating. Occupants who had agreed to become participants were asked to sign a consent form (see Appendix II). The university ethics board granted approval for the study.

#### **4.5.2 Pre-installation interviews**

In June 2012, two months before the EC window retrofit, preliminary interviews were held. These interviews sought to gather relevant background information about the participants, as follows:

1. Age, gender, work patterns
2. Eye health and vision correction
3. Relevant health conditions
4. Satisfaction with their current office environment, in terms of visual comfort, thermal comfort and other relevant factors.
5. Any particular visual comfort issues in their current office, *e.g.* recurrent glare problems at certain times of the day/year.
6. Individual preferences and sensitivities with regards to lighting and visual comfort.

This approach was based on Clear *et. al.* [2006], in which participants filled out a “screening questionnaire” before entering the test room, which included questions about their personal data, eye health and sensitivity to various environmental parameters. For this study, it was decided to gather the information during a one-to-one interview in a separate meeting room. Thus, as well as a means of collecting the required information listed above, these interviews were an opportunity for the researcher and participants to meet in person, for mutual familiarisation and to allow participants to raise any concerns in a private setting, away from the distractions of their office. As such, these interviews were a key step in the process of engagement with the participants.



The interviews were structured, with the majority of questions taking the form of a scaled response questionnaire filled in by the interviewer. The format also allowed for additional notes and comments to be added. The questions were largely based on Clear *et. al.* [2006]. Full details of the questions used in the preliminary interviews can be found in Appendix III.

### **4.5.3 Pre-installation interviews results**

#### *General information*

The four participants were females aged between 30 and 59. Three (based in room B) worked full-time, whilst the participant from room A worked part-time (two to three full days per week). Three out of the four participants reported that they wore glasses or contact lenses. None reported colour blindness.

Participant B2 reported a visual problem that was a symptom of a wider chronic health condition. As well as disturbances to her vision, she felt that it caused her to be more sensitive to light and affected other aspects of her comfort at work; in particular, sensitivity to heat and cold, and fatigue. The other participants reported no visual or relevant health issues.

The following sections give an overview of the results of the other interview questions. The detailed results of the scaled response questions can be found in Appendix IV.

#### *What makes a pleasant office environment?*

Under the heading “What makes a pleasant office environment?”, participants were asked to indicate the importance of 12 different items. All participants rated temperature control, good lighting, windows, controllable windows and controllable lighting as important or very important. Two rated a view as important.

### *Sensitivity to environmental conditions*

Participants were asked to rate their level of sensitivity to 6 different items, and about their preferred office light level. All participants paid particular attention to the issue of glare. Participant A1 commented that glare from direct sun gives her a headache, and participant B1 commented that her computer monitor regularly received direct sunlight, which she was able to control successfully using the window blinds. Participant B2 commented that her preferred lighting level was low because she favours soft, indirect lighting. Participant B3 also mentioned that she regularly receives direct sun on her computer monitor, which she controlled successfully using the blinds. Participant A1 and B2 indicated that they were very sensitive to glare, as well as three other aspects: heat (B2), gloominess (A1) and noise (A1 and B2).

### *Satisfaction with current environmental conditions*

Participants were asked about how satisfied they were with their current office, with respect to a number of parameters. There were a total of 13 questions, with two having follow-up questions to give further information.

All participants appeared to be reasonably satisfied with the current office. In terms of lighting, all but one participant felt that the daylight and electric light level in the room was just right; participant B2 felt that the electric lighting was too bright and the daylight too dark. Thermally, there was a perception that the offices were a bit too warm for much of the time, and the opening of windows was seen as important in dealing with this. Some participants reported dissatisfaction with the air conditioning. Participant A1 felt that the air conditioning outlet was poorly positioned, and she didn't think it was used much, with the windows being opened instead.

All participants indicated that they experienced glare from the windows at least sometimes. Participant A1 chose "All the time", and commented that she experienced a bright patch on her computer screen, which she resolved using the window blinds. Participant B1 chose "Sometimes", adding that glare from windows was controlled successfully using the blinds. Participant B2 chose

“Often” and added that she would experience direct sun on her face if not for the blinds. Participant B3 chose “Often” but commented that the blinds were effective at dealing with this. Three of the participants (A1, B1 & B3) indicated that they sometimes experienced reflections on their computer screen, and they were questioned further about the most common source of these reflections. They were asked to choose between “Windows”, “Ceiling lights”, “Bright patch on wall” and “Other”, and all three chose “Windows”.

In a separate question, participants were asked how often they adjusted their window blinds, choosing between four responses: “Never”, “Rarely”, “Sometimes” and “Often”. Participant A1 chose “Often”, adding that the blinds in her room were constantly being adjusted to prevent direct sunlight causing problems with her computer monitor. Participant B1 chose “Rarely”, commenting that the blinds in her room were left closed most of the time, but that if they were adjusted it would be to control glare from sunlight. Participant B2 chose “Rarely”, commenting that the blinds in her room were kept in the same position most of the time, with the roller blinds on the large window half way down to prevent direct sun on the side of her head. Participant B3 chose “Often”, indicating that glare from sunlight was a problem.

In another question, participants were asked whether they thought the room was “Predominantly lit by the ceiling lights”, “Lit by a combination of ceiling lights and daylight from windows”, or “Predominantly lit by daylight from windows”. Three participants chose “Lit by a combination of ceiling lights and daylight from windows”. Participant B2 chose “Predominantly lit by ceiling lights”, adding that she would like the daylight to dominate more, so that the electric lights could be switched off more of the time.

## **4.6 Summary**

A site for the EC glazing retrofit and research study was identified that was suitable for a number of reasons. A key factor was that the rooms had large areas of southeast facing glazing that was exposed to direct sun all year round and was in need of replacement. Furthermore, it was a typical UK office, continuously occupied with administrative staff carrying out typical office work tasks. This, coupled with the zoning and control system setup of the new windows, facilitated the study by allowing the effects of EC glazing upon the occupants to be studied over a long term period.

As a real-world setting occupied by busy staff, the study site imposed a number of constraints upon the data collection. Thus, the data collection methodology was shaped by the site as well as the aims of the research enquiry (i.e. the research questions), and this will be described in the next chapter.

## **Chapter 5**

### **Data collection design**

The research background, described in Chapters 1 and 2, illustrated the need for a new study of EC glazing that considered the effects of EC glazing on occupants in a real world setting over a long-term period, a number of research questions were defined at the end of Chapter 2. In Chapter 3, the methods employed in previous studies of occupant response to shading systems were described, pointing to the need for a mixed methods approach, encompassing physical measurements and occupant-based data collection using self-report and observational techniques. In the previous chapter, the study setting was described, including the specification and performance characteristics of the EC windows that were installed during the window retrofit. This real world setting necessitates a sensitive approach to the data collection, responding to the needs of the occupants during the study, as well as the aims of the research enquiry.

In this chapter, the philosophical assumptions used in this study are described, highlighting the rationale for a flexible approach that mixes quantitative and qualitative data collection. This is followed by a detailed description of each element of the data collection, illustrating how these elements work together to form a multi-faceted understanding of the occupant experience of EC glazing.

#### **5.1 Philosophy and typology of the study**

##### **5.1.1 Philosophical assumptions used in this study**

This research is socio-technical in nature, as it concerns both the performance of a technology and the experience of humans interacting with it. Thus, it contains elements of both the natural and the social sciences, and is therefore interdisciplinary.

A positivist approach, which assumes an objective reality, serves the purposes of natural science research well. Positivism assumes that the laws governing the processes being studied exist independently of the perception of human beings,

and can therefore be studied under controlled conditions using a classical hypothesis-testing approach [Robson, 2002]. However, in studies that involve the perception of humans, positivism often breaks down for a number of reasons, such as the following (based on Robson, 2002, page 23):

- Reality cannot be purely defined objectively, but must be recognised as being at least partly subjective.
- The emphasis placed by positivism on quantitative research restricts experience, because the real meaning of human behaviour cannot be explained fully using quantitative methods.
- According to the principles of natural science, research participants are seen as scientific objects that are sources of data. This perspective does not recognise the engagement between researcher and participant.
- Positivism strives towards objectivity, but even under controlled conditions objectivity is not guaranteed because the perceptions and meanings of the researcher penetrate the research process in many ways.
- In social science, the personal involvement of the researcher is required in order to interpret the response of the participant.

Relativism lies at the other end of the philosophical spectrum, and is based on the view that there is no reality except that perceived by human beings, and therefore that reality is subjective and does not exist independently of human thought. This approach lends itself more readily to social science-based studies since it respects the unique perspective of each individual. However, in its extreme form, it fails to allow for the existence of some underlying reality. The main criticism of the relativist philosophy is that it is fundamentally unscientific [Robson, 2002].

Robson [2002] asserts that critical realism “can provide a model of scientific explanation which avoids both positivism and relativism.” The central tenet of this philosophy is that the scientific model is context-dependent. This philosophy recognises the existence of an external reality, and further that the role of the scientist is to explain this reality by developing theories about the phenomenon being studied. As he states:

“Following the realist path effectively rephrases the question from ‘What will produce the greatest overall change?’ to ‘What works best, for whom, and under what circumstances?’” [Robson, 2002, page 39].

Pragmatism allows for the inclusion of both qualitative and quantitative methods; a step that is necessary in this research since the sources of data includes both measurements of the physical environment and data from human participants [Morgan, 2014]. In real world research, a pragmatic approach is almost inevitable, as it is flexible enough to allow for the open and unpredictable nature of the setting. With this philosophy, a combination of methodological approaches can be used, as befits the research questions and limitations of the setting.

The approach taken in this study is aligned to critical realism, but could also be said to be pragmatic as it combines methods to suit the objectives of the study. Generalizability is limited by the small sample size in this study, and hence the findings must be viewed in their context, allowing informed speculation about the possible implications for other applications or contexts.

### **5.1.2 Case study approach**

Yin [2009] describes a case study as “an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context”. A case study approach was selected as the most appropriate for this investigation, for a number of reasons:

#### *Limited number of participants*

This study involves a small sample size and limited physical size (*i.e.* two four-person offices). Possible locations for the study were restricted to a small number of suitable sites, and once a site had been selected, the study was limited to the individuals working within that space. The idea of involving other participants was quickly discounted for the main part of the study, because this does not meet the objective of understanding the experience of users of electrochromic glazing within their normal work environment. Therefore, the

research strategy could not easily involve a large sample, nor could it adopt an experimental approach using samples and controls. The sample in this case is one determined by the circumstances: the number of occupants of those rooms who were willing to participate in the study for as long as possible within the duration of the study.

### *The need for a flexible study design*

The nature of this research is fundamentally open and exploratory, due to the lack of existing models for occupant interaction with EC glazing in a real-world setting. The approach used here must be flexible enough to accommodate unforeseen events, and indeed to incorporate these into the research if appropriate.

### *Context & depth of inquiry*

The “real-life context” cited by Yin would seem to be an accurate description of this study. The longitudinal nature of this investigation, together with the repeated probing on a variety of issues, makes this study one in which it is possible to achieve an in-depth understanding of the subject.

### *Multiple sources of evidence*

As previously described, this study relies on data from multiple sources, some of which yield quantitative data and some qualitative data. In Yin’s view, a case study is one that “relies on multiple sources of evidence, with data needing to converge in a triangulating fashion” [Yin, 2009, page 18]. A common misconception of the case study method is that it includes only qualitative data. However, Yin states that the case study as a research method “can include, and even be limited to, quantitative evidence” [Yin, 2009, page 19]. Note that Yin’s definition of the case study is one that applies in the context of the social sciences. However, as previously described, this study is socio-technical in



nature, and thus contains elements of both social and natural science. Therefore it is considered that these definitions are valid for this study.

This study is considered to be a single case, with the two offices and the four participants as embedded units of analysis. The single case design is justifiable because it meets several of the conditions cited by Yin [2009, page 52], such as the unique circumstances (the first non-residential EC glazing installation in the UK) and the longitudinal nature of the study.

### **5.1.3 Mixed methods approach**

The combination of both qualitative and quantitative methods has many advantages in real world research, such as (based on Robson, 2002, page 372):

- It allows triangulation of data from different sources.
- It facilitates interpretation of results: Quantitative methods are good at finding relationships between variables, whilst qualitative methods can help to develop explanations for these relationships.
- Qualitative methods often focus on events happening on a small scale, whilst quantitative methods can describe the bigger picture. A mixed methods approach allows useful integration of the micro and macro scales.

#### 5.1.4 Summary

In summary, this study can be characterised as shown in Table 5.1:

**Table 5.1 Study typology**

Real world	The setting for this study is a real and “ordinary” office, to meet the objective of understanding the effects of electrochromic glazing in a real world application.
Socio-technical	The research concerns the physical effects of the technology as well as the perceived effects on the human end-users of the technology.
Mixed methods	The study uses both quantitative and qualitative methods to study data from a number of different sources.
Pragmatic and critical realist	The philosophy of research recognises the subjective reality experienced by the occupants as well as the existence of some objective reality that can be used to explain the relationships between variables.
Case study	The research is centred on a small number of people over a long-term period. It is investigatory in nature and uses approaches covering a number of perspectives.
Longitudinal	Data are collected over a period of at least 12 months, to encompass a range of seasons (sun positions and weather conditions).

## **5.2 Data collection overview**

### **5.2.1 Aims of the data collection**

The main aim of the data collection is to address the research questions described in Chapter 2. In this study, the data collection also needed to allow for some explorative elements, given the small body of previous research into occupant response EC glazing (Chapter 2) and thus the absence of a theoretical framework within which to present a hypothesis-testing model. Finally, the data collection design needed to respond to the constraints of the real world setting.

The data collection programme was layered, with the aim of collecting data at a useful level of depth and frequency, in order to allow a realistic picture of the users' experience to emerge. The small number of participants in this study put an emphasis on the density of observation. The main challenge of the study design was to achieve a balance between minimising participant burden on one hand, whilst capturing good quality information at regular enough intervals [Krosnick, 1999]. Hence, the data collection combined several instruments, each with a different collection frequency and level of detail.

### **5.2.2 Data sources and data types**

Table 5.2 shows how the data collection was shaped, by considering what kind of data, of the three types identified in Chapter 3 (self-reported, observed and measured), would be required to answer each of the research questions. It can be seen that a combination of data types is required to address each research question; that is, that data obtained from one source alone is not adequate to answer questions. It also shows that measured data must be intersected with another data type in order to provide the information needed. Considering that the overarching enquiry is about the experience of the occupant, it stands to reason that participant-originated data should be the main focus of the analysis, with measured physical data providing context and allowing further exploration of the relationships between measured and perceived parameters.

**Table 5.2**      **How the data collection relates to the research questions**

		Research Question	Data needed		
			Self-reported	Observed	Measured
Visual comfort	1.1	How did EC glazing affect lighting conditions in the space?	✓	✓	✓
	1.2	What were occupants' experiences of visual discomfort?	✓	✓	
	1.3	How did occupants respond to visual discomfort?	✓	✓	
	1.4	Can data from a mixed methods study be used to link measured lighting conditions with occupants' perceptions?	✓	✓	✓
Glazing colour	2.1	How did the glazing tint colour affect the view through the window and the appearance of colours in the room?	✓		✓
	2.2	How did the glazing tint colour affect the occupants in non-visual ways?	✓		✓
Retrofit	3.1	What are the practical issues relating to the installation and commissioning?	✓	✓	
	3.2	How did the retrofit and post-installation period affect the overall user experience?	✓	✓	
Controls	4.1	What were users' perceptions of the control interface and different control modes?	✓	✓	
	4.2	How responsive did users find the system to manual inputs and changing external conditions?	✓	✓	✓
	4.3	How should the control algorithm be optimised to suit the site and users?	✓	✓	

Following on from Table 5.2, Table 5.3 shows how the data collection was further developed by the identification of specific data sources, resulting in a mixture of qualitative and quantitative data.

**Table 5.3      Data sources and types**

Source type	Data source	Data type
Self-reported	<ul style="list-style-type: none"> <li>• Daily feedback</li> <li>• Ad-hoc (informal) feedback</li> <li>• Questionnaires</li> <li>• Interviews</li> </ul>	Qualitative & Quantitative
Observed	<ul style="list-style-type: none"> <li>• EC window data (manual controls use)</li> <li>• Blinds use data</li> <li>• Field diary</li> </ul>	Qualitative & Quantitative
Measured	<ul style="list-style-type: none"> <li>• Internal illuminance/luminance</li> <li>• External illuminance</li> <li>• Sun position</li> <li>• EC window data (window states)</li> </ul>	Quantitative

### 5.2.3 Sampling intervals

The frequency of data collection varied greatly between different data sources, ranging from 1 second to every three months. The interval of measurement was often constrained by the need to balance participant engagement with the amount and quality of data that could be obtained. This was particularly the case where the data source was the participant (as for self-reported data), or where the data were collected by obtrusive measurement equipment. In other cases, the sampling interval was only limited by the volume of data that could be stored, with a more frequent interval imposing no more inconvenience to occupants than a less frequent interval. Overall, the data collection programme devised for this study aimed to capture enough data to address the research questions, whilst maintaining as high a level of participant engagement as

possible to ensure that the quality of the data, and indeed the viability of the study as a whole, was preserved. The sampling intervals used for each element are summarised in Tables 5.4 (for self-reported data) and Table 5.8 (for physical measurements). The observed data collection was event-based, and therefore did not have a fixed sampling interval, *i.e.* occupant actions were recorded when they occurred.

### 5.3 Self-reported data

The self-reported data collection programme combined four main elements, as shown in Table 5.4. The elements varied in depth of enquiry and collection frequency, with tools aimed at collecting frequent but coarse information being complemented by others aimed at collecting less frequent but detailed information.

**Table 5.4 Self reported data collection summary**

Data collection tool	Collection frequency	Level of detail
Questionnaires	Once per month	Medium
Interviews	Every 3-4 months	High
Daily experience records	Daily	Low
Ad-hoc feedback	Opportunistic	Variable

#### 5.3.1 Questionnaires

The questionnaire was designed to collect a reasonable level of detail whilst still being short enough to be completed relatively quickly. With the exception of the final question, participants were asked to respond to each question in terms of their feelings at that particular moment, in order to allow participants' responses to be linked to measured physical conditions at that time. The last question was asked with respect to the previous two weeks, to gather some additional information about participants' experiences in more general terms.

The questionnaire was aimed at gathering data on the experience of participants with respect to the following:

- (i) Visual comfort
- (ii) Perceived daylight quantity
- (iii) Perception of direct sunlight in the room
- (iv) View through EC window
- (v) Appearance of colours in room
- (vi) Thermal comfort
- (vii) Alertness/Tiredness
- (viii) Wellbeing
- (ix) Overall impression

These aspects were chosen for inclusion in the questionnaire based on a review of previous studies of occupants' experience of shading devices, lighting conditions and visual comfort in daylit spaces, as described in Chapters 2 and 3. Table 5.5 gives an overview of the key studies that were used as a basis for the questionnaire design. Survey questions used by others to study these constructs were identified as part of the literature review. The highlighted cells in Table 5.5 indicate measures that were chosen for use in this questionnaire based on a previous study. The extent to which the final questions resembled those used in previous studies varies widely; some questions are almost identical to the one used in a previous study, whilst others are only loosely based on the previously used question. In some cases, a completely new question was devised to assess a particular aspect, for example if it was felt that none of the previous study questions were entirely suitable.

**Table 5.5** Survey questions used in previous studies. The shaded cells indicate measures (questions) chosen for inclusion in the questionnaire.

Construct (measure)	Aries <i>et al</i> 2010	Arsenault 2011	Clear <i>et al</i> 2006	Hygge <i>et al</i> 1999	Osterhaus 2005	Laurentin 2000	Smolders et al 2012	Velds 2002	Vine <i>et al</i> 1998	Vischer <i>et al</i> 2005	Zinzi 2006
Light level	×	×	×	×	×			×	×	×	×
Light distribution		×	×						×		×
Glare sensation		×	×	×	×			×	×	×	×
Screen reflection	×		×	×	×			×	×		
Daylight quantity		×			×				×		
Predominance of daylight											×
Effects of direct sunlight	×								×		
Satisfaction with view			×						×		
Distortion of view											×
Perception of colours		×	×								×
Temperature			×		×				×	×	
Unwanted heat from sun	×			×				×			
Sleepiness (KSS)		×					×				
Emotional state					×						
Mood (POMS)							×				
Pleasantness						×					
Reliance on electric lighting				×	×				×		×
Satisfaction with controls			×								×



Constructs such as visual comfort, perceived daylight quantity, perception of direct sunlight in the room and overall impression were included to assess how EC glazing affects these aspects. The scale used to assess the severity of glare (Noticeable – Acceptable – Uncomfortable – Intolerable) was based on the one used in Clear *et. al.*'s questionnaire [Clear *et. al.*, 2006], which was in turn based on Vine *et. al.*'s study [Vine *et. al.*, 1998]. Different scales have been used to record subjective glare ratings in other studies, however there is some debate as to which words to use to label the categories and borderlines [Fisekis, 2003].

Items such as view through the EC window and appearance of colours in the room are more specific to the study of variable tint glazing, and were included to gain an understanding of how the tinting of the glass might affect the ability to see clearly through the window and the colour rendering of surfaces in the room. Alertness (tiredness) and wellbeing were included to enable the investigation of other, non-visual, effects of the tinting of the glass on the occupants. Thermal comfort was included to allow perceived room temperature to be monitored and linked to measured conditions at a given time, and also because unsatisfactory thermal conditions might influence the perception of other aspects of the environment [Laurentin *et. al.*, 2000].

For the “Wellbeing” construct, two measures were originally chosen: Emotional state and Mood. These are only two of many possible measures of wellbeing; however, in the context of this study, it was considered that an assessment of mood would be sufficient to capture some information about the current condition of a participant's psychological state. The Profile of Mood States (POMS), used by Smolders *et. al.* [2012], was considered too long for use in the questionnaire, so the shorter Positive and Negative Affect Schedule (PANAS) tool [Watson *et. al.*, 1988] was considered. However, pilot tests on three colleagues in the research department indicated that it made the questionnaire unacceptably long. Thus, the assessment of mood was removed from the questionnaire and instead one question about emotional state, based on Osterhaus [2005], was included.

Two measures were identified in the literature review that were not considered to be appropriate for inclusion in the questionnaire, but were included in the

interview. One was the assessment of participants' experience of the EC window control system settings and interface, and the other was the perceived reliance on electric lighting. These measures were not included in the questionnaire because questions about these aspects would not easily fit the time-linked format, *i.e.* with reference to that particular moment. It was considered that these aspects would be best assessed during interviews, where there would be an opportunity to discuss things with reference to the past few weeks or months.

### *Final questionnaire design*

Table 5.6 shows the measures chosen for each construct, and how these map to items in the final questionnaire. Note that questions 1 and 2 are administrative (participant ID number and room number) and are not included in this table. The full questionnaire can be found in Appendix V.

Ultimately, the design of the questionnaire involved a balance between the number and depth of questions and the effort to ensure that it could be completed within a reasonable time. It was decided that 10 minutes was about the maximum length of time participants would be expected to spend completing the questionnaire. The final questionnaire consisted of a maximum of 20 questions. (The number of questions could be less than 20 due to some questions being conditional, *i.e.* only asked if the response to the previous question was "yes".) All questions were required to be answered before the participant could proceed to the next question, and space for text was provided after each question so that additional comments could be made if desired. Once the first questionnaire responses came back, time stamps on the start and finish of each submission indicated that the questionnaire was typically completed in less than 5 minutes.

Questions were ordered so that the most straightforward questions, such as those about lighting and glare, appeared first. Questions that might be perceived by participants as more personal, such as those about alertness and emotional state, appeared later. A question about the extent to which the participant felt

that direct sunlight had hindered their work during the past two weeks was put at the end since it didn't follow the format of the other questions.

As shown in Table 5.6, most questions had a multiple-choice format (one choice only), and in several cases the choices were presented in the form of a 5-point bipolar scale. Typically, there were labels for only the extreme end categories (*e.g.* "Too hot" or "Too cold") and the centre category (*e.g.* "Just right"). This approach was considered to provide an appropriate range of response categories to allow participants to record their experience, and was used by Clear *et. al.* [2006] and others.

**Table 5.6** Questionnaire constructs, measures and questionnaire items. *Dash (-) indicates response categories without a label.*

Construct	Measure	Question	Response options	Q no.
Visual comfort	Perceived light level	How would you describe the total light level (from the windows and overhead lighting together) in your office at the moment?	Too dark/ - /Just right/ - /Too bright	3
	Perceived light distribution	How would you describe the distribution of light in your office at the moment?	Poorly distributed/ - /Just right/ - /Nicely distributed	4
	Experience of glare from screen reflections	At the moment, are you experiencing any reflections on your computer screen? (If yes, asked to identify source)	Yes/No Windows/Ceiling lights/Bright patch/Other	7 8
	Experience of direct glare	At the moment, are you experiencing glare caused by light shining directly into your eyes? (If yes, asked to identify source and rate severity)	Yes/No Windows/Ceiling lights/Bright patch/Other Noticeable/Acceptable/Uncomfortable/Intolerable	9 10 11
Perceived daylight quantity	Perceived dominance of daylight or electric light	At the moment, do you think that the room is: (Multiple choice)	Predominantly lit by the ceiling lights/ Lit by a combination of ceiling lights and daylight from windows/ Predominantly lit by daylight from the windows	5
	Perceived amount of daylight	How would you describe the level of daylight in your office at the moment?	Too much daylight/ - /Just right/ - /Too little daylight	6

Construct	Measure	Question	Response options	Q no.
Alertness	Karolinska Sleepiness Scale (KSS)	Using the scale below, please indicate how tired or alert you currently feel.	Extremely alert/ - /Alert/ - / Neither alert nor sleepy/ - /Sleepy, but no difficulty staying awake/ - / Extremely sleepy, fighting sleep	12
Wellbeing	Self-reported emotional state	Overall, how would you describe your emotional state at the moment?	Excellent/Good/Average/Poor/Very poor	13
View through window	Perceived clarity of view through the window	How satisfied are you with the clarity of the view through the windows at the moment?	Very dissatisfied/ - /Neither satisfied nor dissatisfied/ - /Very satisfied	14
	Perceived ability to assess weather by looking through the window	At this moment, how easy is it to gauge the weather outside by looking through the window?	Very difficult/ - /Neither difficult nor easy/ - /Very easy	15
Thermal comfort	Perceived temperature	How would you describe the temperature in your office at the moment?	Too cold/ - /Just right/ - /Too hot	16
	Perceived solar overheating	If the sun is coming into your room at the moment, please indicate whether the heat of the sun is causing discomfort for you. If there is no sun coming in, please choose N/A.	Very uncomfortable/ - /Neither comfortable nor uncomfortable/ - /Very comfortable/N/A	17
Overall impression	Perceived pleasantness of room environment	Using the scale below, please indicate how pleasant you find your office at the moment.	Very unpleasant/ - /Neither pleasant nor unpleasant/ - /Very pleasant	18
Appearance of colours in room	Perception of colours in room	Please use the scales below to describe the appearance of colours in your office at the moment.	Natural: Not at all/A little/Moderately/Quite/Very much so	19a
			Vibrant: Not at all/A little/Moderately/Quite/Very much so	19b

Construct	Measure	Question	Response options	Q no.
Adverse affects of direct sunlight	Occurrence and severity of any problems caused by direct sunlight (during recent past)	During the past two weeks, please indicate to what extent your work was hindered by direct sunlight coming into your office using the scales below.	Heat of the sun:	20a
			Not at all/A little/Moderately/Quite a lot/Very much	
			Direct sunlight on your desk:	
			Not at all/A little/Moderately/Quite a lot/Very much	20b
			Reflections on your screen:	
			Not at all/A little/Moderately/Quite a lot/Very much	
				20c

### *Administering the questionnaire*

The questionnaire was sent to participants via email using SurveyMonkey once per month. Initially, the questionnaire was issued every two weeks, but after a review in June 2013, it was decided to reduce the frequency to once per month, due to feedback indicating that some participants found the fortnightly request too onerous. Furthermore, the response rate had been generally poorer than expected, and with so few participants, this had had a considerable impact. A reduction in frequency was agreed with the understanding that participants would make a greater effort to respond, and that more effort would be focussed on chasing up missing questionnaire responses within the longer time period between requests.

In a covering email, and again within the questionnaire, participants were instructed to complete the survey in one sitting (*i.e.* not to leave the survey and come back to it later) and during daylight hours. This was to ensure that they could respond to each question in terms of how they felt at that particular moment, and allow their responses to be associated with measured conditions at or around that time. It was considered that, although it would be useful to request that participants complete the questionnaire at specific times (*i.e.* to coincide with particular external conditions), it was likely to be perceived by participants as too onerous that they should be asked to abandon their current work task in order to complete the survey. Thus, they were given a period of two weeks in which to complete the survey at a time convenient to them. This approach was intended to decrease the potential for participant disengagement and increase the likelihood of response.

### **5.3.2 Interviews**

Interviews with occupants were an essential part of the data collection in this study, since they produce first-hand accounts of the users' experiences. A semi-structured format was used because, being more flexible than structured interviews, it allows for the exploration of "unscripted" but relevant topics as they arise in the course of natural dialogue. Scaled responses were not

considered appropriate because they might prevent the flow of conversation. Furthermore, the questionnaires, rather than the interviews, were seen as the natural place to record quantitative self-reported information in this way.

The areas explored in the interviews are as follows:

- Visual comfort
- Thermal comfort
- User controls and settings
- Glazing colour
- Perception of view through window
- Overall satisfaction

These aspects were chosen for inclusion in the interview based on a review of previous studies of occupants' experience of shading devices, lighting conditions and visual comfort in daylit spaces (see Table 5.5). The interviews were used to explore many of the same issues as the questionnaire, but in more depth. As such, most of the interview questions are more open versions of those used in the questionnaire. Questions were asked with respect to the recent past (*e.g.* the last few weeks) or "in general". Several questions were loosely based on survey questions used by Clear *et. al.* [2006] and Zinzi [2006]. However, as neither of these studies used interviews, the wording was formulated to suit an interview format and developed where necessary to suit the subject matter and context.

The wording of the questions, and the order in which they were asked, varied slightly as the data collection progressed. Changes were made in response to issues that arose at various points. For example, after changes or adjustments were made to the control system, questions about the control system were given a higher priority and therefore asked earlier in the interview. Also, the wording of the questions could be made more specific to the situation.

Table 5.7 contains the scripted parts of the interview, including the main questions asked. It also shows the literature on which each question was based, where applicable.



### *Interview administration*

Interviews needed to be held regularly enough to capture the participants' perspective as time progressed, taking account of seasonal changes and the like. On the other hand, it was important that interviews were not unduly long and that they were not conducted too often as to represent a nuisance to participants. Thus it was decided that interviews would be held approximately every three months. Interviews were conducted face-to-face on an individual basis in a private meeting room. It was considered that participants might be more open and honest about their experience in this setting rather than, say, in a group format (*i.e.* a focus group).

The interviews were audio recorded, and minimal notes were made by the interviewer to encourage a more natural and open dialogue with the participants. The preamble and closing remarks were scripted, and for the main body of the interview, a mind map of interview questions (Appendix VI) was used to ensure that all the main topics are covered. This approach meant that all questions and sub-questions were on one sheet, thus avoiding the need for the interviewer to search through several pages to find questions. The mind map also facilitated a more organic approach, allowing flexibility in the ordering of questions, depending on how the interview unfolded. The wording of the main questions was scripted in order to ensure consistency and to avoid leading or closed questions where possible. Although not scripted in the same way, sub-questions were included in the mind map to serve as prompts in cases where the participant struggled to respond or responded in a closed manner, to assist the interviewer in probing further on a particular question.

**Table 5.7 Interview script**

<b>Opening remarks</b>		
The purpose of this interview is to see how you've been finding things since the last interview. I'm really just interested in your experience; there are no right or wrong answers. I'd like to remind you that everything we talk about will be kept confidential and anonymised in any publications.		
To make it easier for me to listen to you and focus on what you're saying, I would really like to record the interview – is that ok with you? As soon as I'm finished transcribing, I will destroy the recordings. It's just so I don't have to spend the whole time writing notes; it will make it much easier for me to really listen to what you're saying, and means I won't miss anything important.		
<b>1</b>	<b>Window control system and user interface</b>	<b>Literature</b>
1.1	Have you been using the wall switches much to control the window tint?	
1.2	With the current settings, the bottom row of panes is usually kept clear, while the upper panes tint if it's sunny. How is that working for you?	
1.3	How have you been finding the response time of the window?	Zinzi, 2006
1.4	Is there anything else you'd like to mention about the window controls?	
<b>2</b>	<b>Glazing colour</b>	
2.1	When the windows are tinted, do you think it affects the colours in the room in any way?	Clear <i>et. al.</i> , 2006
<b>3</b>	<b>View</b>	
3.1	When the glass is tinted, how does it affect your ability to see through the window?	Clear <i>et. al.</i> , 2006
<b>4</b>	<b>Visual comfort</b>	
4.1	In general, during the past few months, how have you found the light level in your room?	Clear <i>et. al.</i> , 2006
4.2	Have you been able to work without the lights on at all?	Zinzi, 2006

4.3	Have you had any problems with the sun shining directly into your eyes?		
4.4	Thinking about your computer screen – have you had any problems with seeing reflections on your screen?		
<b>5</b>	<b>Thermal comfort</b>		
5.1	In general, how have you found the temperature in the room during the past few months?		Clear <i>et. al.</i> , 2006
5.2	When we have sunny weather, does the tinting affect your perception of how sunny it is outside?		
<b>6</b>	<b>Overall satisfaction</b>		
6.1	Overall, how have you felt about the windows during the past three months?		
6.2	Is there anything else that you would like to tell me about?		
<b>Closing remarks</b>			
Thanks very much for your time and for your continued help with the study.			

### 5.3.3 Daily experience record

It was not practical to administer questionnaires or interviews at high frequency due to risk of participant fatigue in this long-term study. Thus, a daily experience recording technique was developed in order to allow regular self-reported data capture at a short time interval.

The daily experience record sheet contained a table similar to a monthly calendar page, on which participants could mark their general satisfaction with the EC glazing performance at the end of each day using happy/neutral/sad face emoticons. An example of a (blank) daily experience record sheet is shown in Figure 5.1.

Although recorded at a high frequency, this approach is minimally intrusive, as participants can simply circle the relevant symbol before they leave the office. There is also a space for comments, which participants regularly used to convey additional detail. Although the data gathered with this method are rather coarse, it was intended to facilitate an exploration of whether general occupant perception can be linked to average meteorological conditions and/or sun angles (*i.e.* seasonal variability), and thus give an indication of how EC glazing performance varies depending on weather and season.

A review of the data collection in July 2013 highlighted a lower than expected rate of completion of the daily experience record sheets. Participants often forgot to complete them, and one of the main reasons is that it could be easily lost amongst other paperwork on their desks. Following the review, the forms were printed on yellow coloured paper, so that they were less easily misplaced. In addition, an automatically generated email was sent every week reminding participants to fill in their record sheets. The response rate did improve slightly, but remained less than ideal from the point of view of data collection.

How were the windows for you today?

Name: \_\_\_\_\_

Please circle the appropriate icon.





























































Week commencing	Monday	Tuesday	Wednesday	Thursday	Friday
2 Dec 2013	   Comment:	   Comment:	   Comment:	   Comment:	   Comment:
9 Dec 2013	   Comment:	   Comment:	   Comment:	   Comment:	   Comment:
16 Dec 2013	   Comment:	   Comment:	   Comment:	   Comment:	   Comment:
23 Dec 2013	   Comment:	   Comment:	   Comment:	   Comment:	   Comment:

Figure 5.1 Example of a blank Daily Experience Sheet

### 5.3.4 Ad hoc feedback

While the use of the first three techniques were designed at the outset of the study, to capture occupant perception data that can be linked with physical measurements, it was found that a further source of data was available: During researcher visits to the study rooms, occupants often provided informal feedback about their experiences. These comments were recorded in a Field Diary, along with other relevant observations made at the time of the visit.

While this ad-hoc occupant feedback has clear limitation in terms of a rigorous analysis, it does provide useful narrative detail that has been used to inform the retrofit process and was found useful in terms of evaluating the study setup and gauging participant fatigue. Moreover, the ad-hoc feedback contributed to the iterative process of refining the data collection methodology, *e.g.* keeping the interview questions relevant and making sure additional issues could be explored in the interviews as they arose. Additionally, this data source was useful for reporting on the retrofit process itself.

## **5.4 Observed data**

The use of EC manual controls or blinds is an important indicator of times when the EC windows in automatic mode alone were not sufficient to meet the needs of occupants. Thus, information about the usage of both EC manual controls (“manual overrides”) and blinds were an important part of the data collection. When combined with data about the physical conditions in the room or self reported data from around that time, this information could give valuable insights about the motivations behind occupant interactions with EC glazing and blinds, and their visual comfort thresholds.

Hence, the observed data collection included a record of occupant interactions with both EC window manual controls and blinds. The Field Diary (section 5.3.4) also contained elements of observed data, as it included observations and notes about the series of events surrounding the EC window installation and the post-installation period.

### **5.4.1 EC window control system data (manual override use)**

From 11<sup>th</sup> April 2013 onwards, all manual inputs to the EC window control system were recorded in the system log. The log contained detailed information about the use of the manual controls as well as the system in general (see section 5.6.3). For each instance that a manual switch was pressed, the following data were logged:

- Time
- Zone
- Number of times the switch was pressed
- Target transmittance (%T) of the manual switch action

Thus, detailed information about each interaction with the EC window controls was recorded, allowing the extraction of quantitative data about the usage of manual controls over the data collection period. This information was also included in the one-day EC window control system summary sheets described in section 5.5.3 and shown in Figure 5.8.

### 5.4.2 Blind use



Blind usage data was collected using a Blinds Diary, which was supplemented by a series of façade photos.



#### *Blinds Diary*

The Blinds Diary was devised as a low-impact solution for recording blind usage that did not require the installation of additional hardware in the rooms. The diary was a one-page pro-forma (Figure 5.2), which was mounted on the wall between the two windows in each room. Participants were asked to fill it in whenever they lowered the blinds during the period April 2013 – March 2014.

**BLINDS DIARY**

*Why did you lower the blinds?*

Date	Time	Reason		
		<i>Please enter the initials of the person affected</i>		
				Other

Key:  The sun is shining into the person's eyes  
 The sun is shining onto the person's computer screen

**Figure 5.2** Blinds Diary

Participants were asked to enter the initials of the person for whose benefit the blinds were being lowered (*i.e.* because it may not have been the person who physically lowered the blinds). This was to ensure that the diary provided a record of not just the times when blinds were lowered, but also details about the reasons why they were lowered. In this way, the level of detail that could be collected using this tool was maximised whilst only requiring minimal input

from participants (*i.e.* to write the date and time, and initials of the affected person in the relevant column).

Blinds diaries were installed in both rooms, but despite researchers' efforts to encourage occupants to use the diary, no entries were made in room A. The occupants cited a lack of blind use as their main reason for not using the diary. Thus, blinds diary data were collected from room B only, with some supplementary information about blind use collected using a series of façade photos, as described below.

### *Façade photos*

A series of photos of the façade were taken between December 2013 and June 2014. These photos give an overview of the pattern of blind usage in both rooms A and B during the data collection period. From these images, the total proportion of window covered by a blind in each room was determined by visual inspection of the digital images, expressed as percentage blind occlusion [Rea, 1984]. An example is shown in Figure 5.3. Automated façade photos were considered, but could not be implemented because a suitable location for a camera in an adjacent building could not be identified.



**Figure 5.3** A sample façade photo and associated blind occlusion



## 5.5 Physical measurements

This part of the data collection involved a wide range of physical measurements inside the room and a number of external measurements to capture weather conditions. Table 5.8 summarises the physical data collection and indicates the sampling interval in each case. Not all of the data collected were analysed, as explained in Section 5.5.4. The shaded rows indicate data that were analysed, whilst the un-shaded rows indicate data that were collected but not used in the analysis.

**Table 5.8 Physical data collection summary**

Measure	Method of measurement	Sampling interval
Visual field luminance data	HDR	Every 30 minutes, weekdays, 0800 – 1800
Workplane illuminance	Illuminance meter and logger	Every 2 minutes
Room temperature	Hobo logger	Every 10 minutes
Heating on/off	Hobo logger	Every 30 minutes
Air conditioning on/off	Hobo logger	Every 30 minutes
Electric lighting energy consumption	Hobo CT + logger	Every 30 minutes
EC window energy consumption	Hobo CT + logger	Every 30 minutes
External vertical façade illuminance	EC window control system	Ranged from 1-60 seconds *
Sun altitude and azimuth	EC window control system	Ranged from 1-60 seconds *
EC window transmittance	EC window control system	Ranged from 1-60 seconds *
EC window control mode	EC window control system	Ranged from 1-60 seconds *
EC window switch mode	EC window control system	Ranged from 1-60 seconds *
External horizontal diffuse illuminance	DMU Weather station	Every 10 minutes
External horizontal direct illuminance	DMU Weather station	Every 10 minutes
External dry bulb temp, wind speed, rainfall etc.	DMU Weather station	Every 1 hour

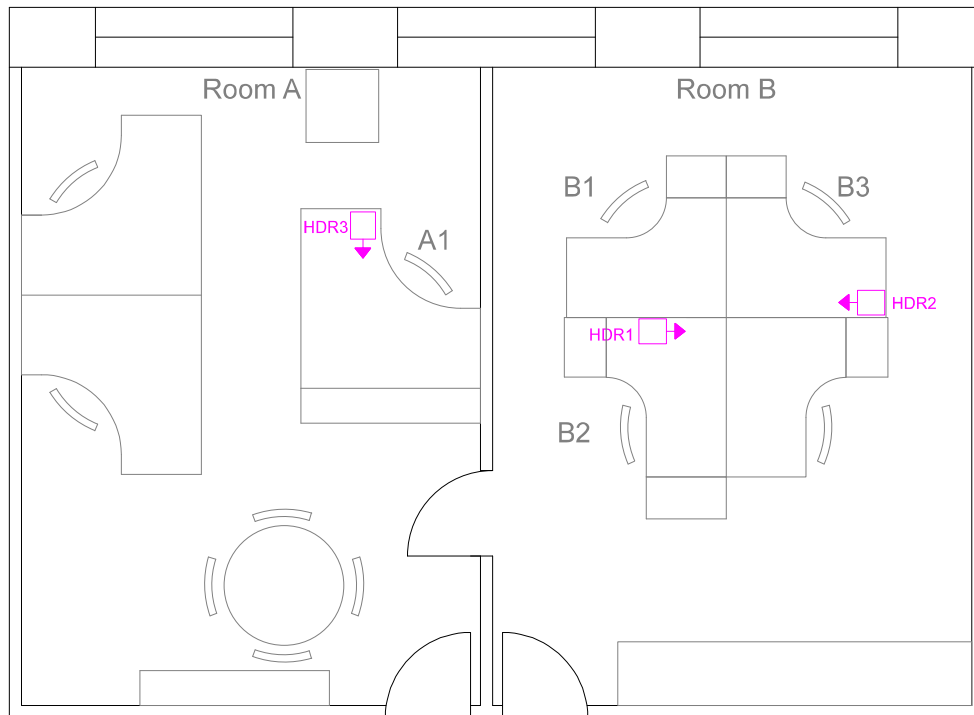
\* The EC window control system logged data at variable intervals – see section 5.5.3.

### 5.5.1 HDR Imaging

High Dynamic Range (HDR) imaging was used to capture quantitative data about the luminous conditions in the room. This technique has been used in a number of previous studies of visual discomfort, as described in Chapter 3, *e.g.* Painter *et al.* [2009]. A number of digital cameras (Canon EOS 400D) fitted with fisheye lenses (Sigma EX DG 1:3.5 mm) were placed in the rooms, each coupled with a computer hard drive (Mac Mini 1.66GHz “Core Duo”). Software installed on the Mac Minis executed the capture of a series of images at different exposures and combined them into a single HDR image. As each HDR file is large (approximately 26 MB), each hard drive could only store a limited number of images before it became full. Thus, an interval of 30 minutes was chosen and it was decided to capture images during working hours only (0800 – 1800 hrs on weekdays).

#### *Camera positioning*

Before the EC windows were installed, possible locations of HDR cameras in the study rooms were thoroughly investigated. If field of view images for each participant were to be collected, it would be necessary to locate a camera at or near each participant’s eye position. However, as this would not be possible over a longitudinal period, it was decided to locate cameras in a suitable nearby position (in the case of room A), or in a position that would cover a field approximate to that seen by more than one participant (in the case of room B). Figure 5.4 shows the locations of cameras in the study rooms (indicated by HDR1, HDR2 and HDR3). Figure 5.5 shows a photograph of one of the cameras (HDR2) installed in room B.



**Figure 5.4** HDR camera positions



**Figure 5.5** HDR2 camera installed in room B

### *HDR data management*

As mentioned previously, the volume of data represented by this part of the data collection was considerable. Thus, a number of steps were taken to manage the collection and storage of the HDR image files. In order to avoid each Mac Mini hard drive becoming full, the data were moved weekly onto a central data collection laptop and backed up on two external hard drives. Each Mac Mini and the central laptop were assigned static IP addresses so that they could be accessed via a local wireless network, and the researcher could transfer the files using the central laptop, as shown in Figure 5.6.



**Figure 5.6 HDR data collection**

In August 2013, some automation was introduced to make the process of HDR data collection less cumbersome. A python script was created to run on the central laptop each night, which accessed each Mac Mini in turn and moved the files to a specified folder on the laptop. This process worked as long as the Mac Minis were connected to the internet and could be found by the script. However, this was often not the case, due to reliability issues with the wireless network. Another script was created that connected to each Mac Mini before the file transfer was due to take place. Unfortunately, the automated file transfer still failed to complete successfully on regular occasions, and the files needed to be

manually transferred. As a result, the HDR data collection remained one of the more labour intensive aspects of the data collection.

#### *Data extraction from HDR images*

In order to allow data from the HDR images to be analysed, a range of luminance metrics was extracted from each HDR image. Existing HDR-based tools, such as Evalglare [Wienold & Christoffersen, 2006], are intended for use with images that represent the field of view of an observer. In this case, since the cameras were not at occupants' eye positions, these tools were not considered suitable for analysis. Also, their applicability for occupants that are not looking directly at the window is questionable [Van Den Wymelenberg, 2014; Konis, 2014; Painter *et. al.*, 2009]. Therefore, other candidate metrics were chosen for extraction from HDR images, as follows:

- Minimum luminance (Min L)
- Maximum luminance (Max L)
- Mean luminance (Mean L)
- Median luminance (Median L)
- Standard Deviation L (Std Dev L)
- Percentile ratio of 75<sup>th</sup> to 25<sup>th</sup> percentile luminance (75:25)
- Mean L of the “front” (window) half of the room
- Mean L of the rear half of the room

These metrics were chosen because they were considered to describe a broad range of luminance-based parameters that could be investigated during data analysis. Some were chosen based on previous studies that investigated relationships between luminance metrics and perceived lighting conditions (self-reported data), such as Konis [2014] and Van Den Wymelenberg [2014].

In order to extract data, each HDR image to be analysed was first compressed using a piece of specialist software. New software was created that converted the compressed image into an array of luminance values per pixel and applied a

correction factor to each pixel to account for the vignetting effect of the lens [Jacobs & Wilson, 2007]. The metrics were then extracted and exported to a spreadsheet. A number of HDR images could be processed at once (*i.e.* batch processing) so that a large amount of data could be generated quickly for analysis.

Luminance data from HDR images could then be compared with data from other sources that occurred around the same time, to investigate possible relationships between the luminance metrics and the perception of an occupant. For example, a participant's response to a questionnaire could be compared with the data from the chronologically nearest HDR image.

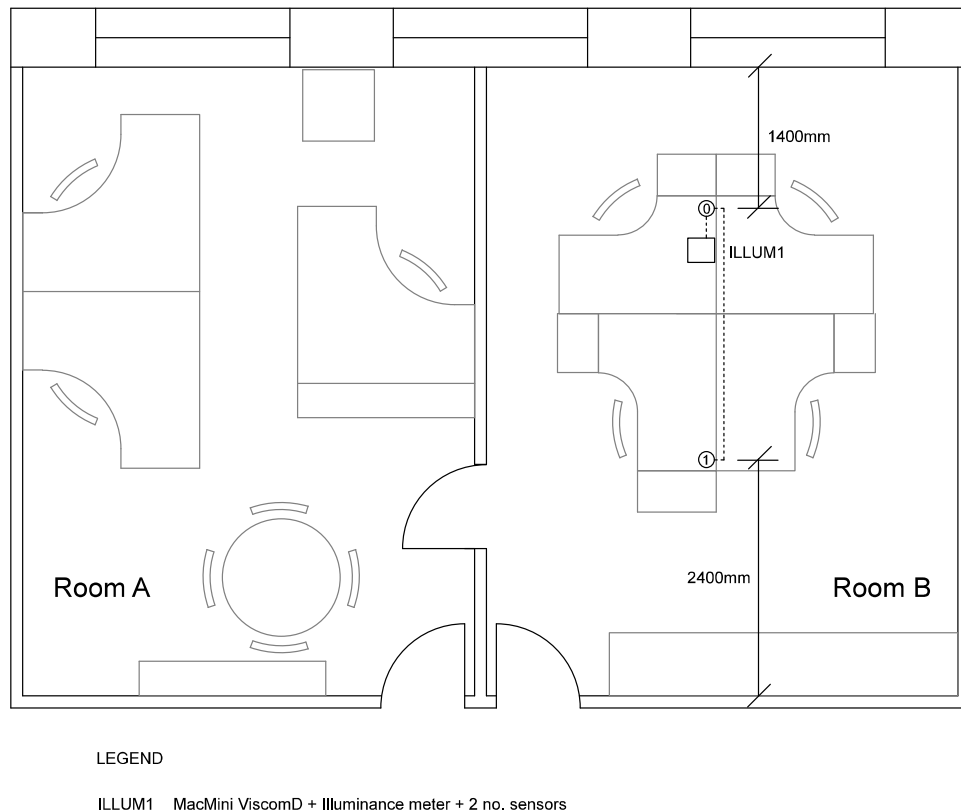
#### *Later changes to HDR camera in room A*

Feedback from participant A1 (room A) indicated that the camera was physically obstructive. The position of this camera was constrained by the room layout, and that area of the room was already quite congested by furniture. From September 2013 onwards, it was agreed that this camera would only be used for periods of around two weeks, at key times during the year, namely the solstices and equinoxes. In between these periods, the camera and associated Mac Mini would be removed from the room. This concession to the participant was balanced with a request for more sustained input to the daily experience sheets and online questionnaires, which did result in more data being provided by participant A1.

### **5.5.2 Interior illuminance measurements**

In addition to the HDR measurements, the illuminance on the workplane was monitored. An illuminance meter (Minolta T10-M), which could be connected to up to ten mini illuminance sensors in series, was used for this purpose. Only one illuminance meter was available, and due to physical constraints, it was not possible to install wired illuminance sensors in both rooms. Thus, only the workplane illuminance in Room B was monitored. Due to the presence of HDR cameras and associated hardware, there were few positions left in which to locate illuminance sensors at desk height. It was decided to place two sensors in

the room, one as close to the window wall as possible whilst still being on the desk, and another further back into the room, as shown in Figure 5.7. The illuminance meter was connected to a Mac Mini (Mac Mini 1.66GHz “Core Duo”), which enabled the illuminance readings from each sensor to be logged in a \*.txt file, producing one file per day.



**Figure 5.7 Desk illuminance logging equipment layout**

Unfortunately, the illuminance logging failed on a regular basis. A number of possible causes were investigated, such as a fault with the USB-serial interface and electromagnetic interference, but it remains unclear why it was so unreliable. As a result, at the end of the data collection period, there were numerous episodes of missing data, and not enough continuous data to be included in the analysis.

### 5.5.3 EC window control system data

The EC window control system log recorded detailed information about each zone at a high frequency. The data captured were as follows:

- Exterior façade sensor reading
- Solar elevation & azimuth
- Control mode (auto, manual or glare) for each zone
- Glazing transmittance in each zone
- Switch status in each zone. If a zone switch was pressed, this included the number of times it was pressed and the target tint level in each case.

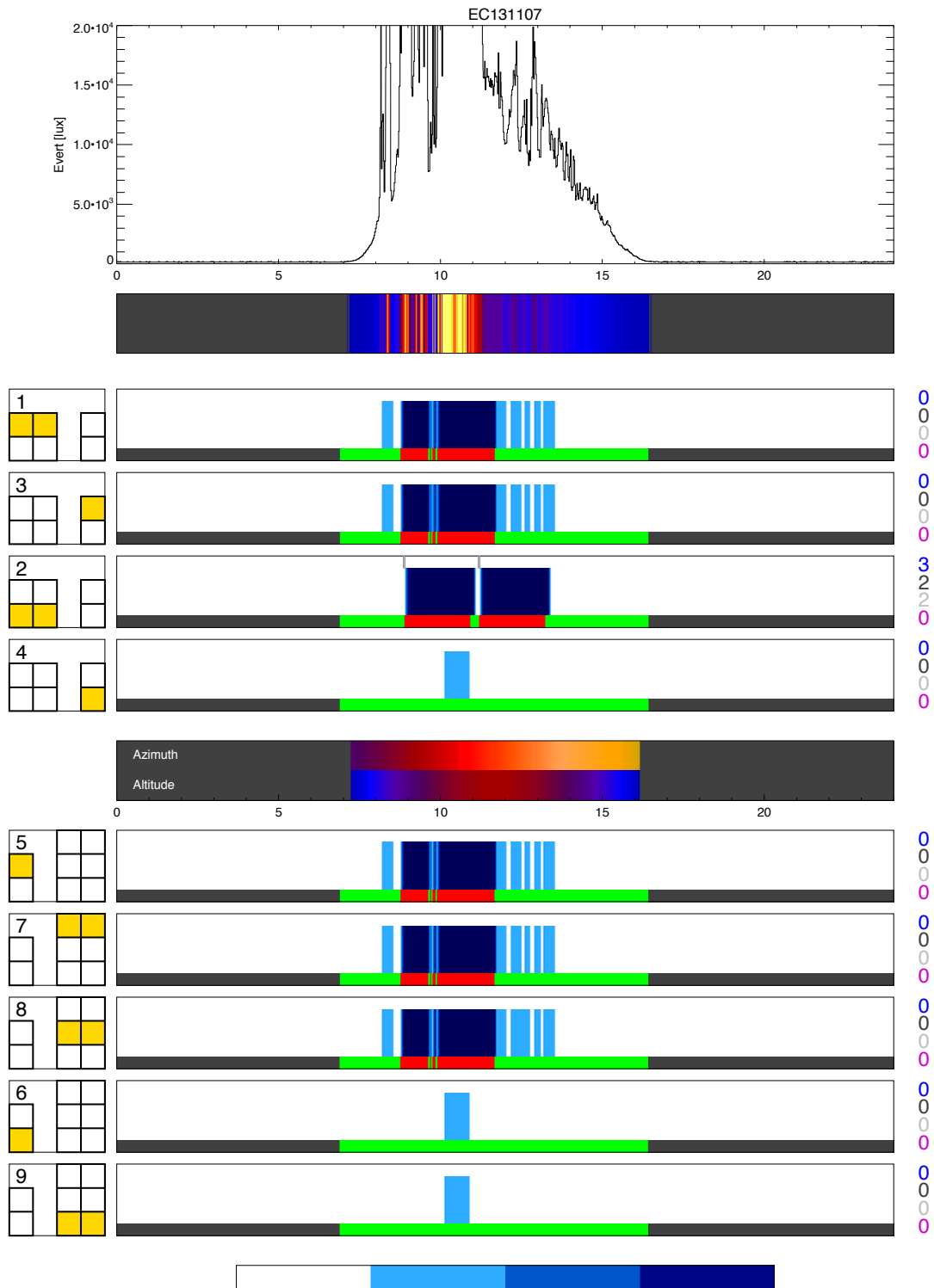
#### *Data acquisition*

After the window installation, a PC laptop was installed in room B that was connected to the window control system. The PC could be accessed via the internet, enabling remote access to the control system by SAGE personnel in the US, as well as researchers within the DMU campus. The intention was that control system data could be pulled from the system by DMU researchers at appropriate intervals. However, this arrangement became problematic due to reliability issues with the software, resulting in periods of missing data. In order to resolve this, and some other control system issues (see Chapter 6), the control system was upgraded to the latest available version in March 2013. From then on, SAGE personnel retrieved data from the system via the PC laptop every week and sent it to DMU. These data were exported in the form of a spreadsheet, with one file generated per day (24 hours). Information was logged at mean intervals of 20-30 seconds. The time step was not regular, due to the fact that the system took readings whenever any of the parameters changed, so it could range from 1 second to 1 minute.

Software code was created to convert the data in a one-day log file into a useful graphical summary sheet, and example of which is shown in Figure 5.8. The summary sheet gives a time series view that shows external illuminance values at the top, against a y-scale and in a colour visualisation (with lighter colours



representing higher values). Below these, the tint settings for the different zones are shown, also against time of day, with darker tints shown as darker blue shaded areas. The squares on the left hand side indicate the zone to which the data refers (zone arrangements are also shown in Figure 4.6). The numbers on the right hand side indicate how often manual overrides occurred in each zone that day. Azimuth and altitude are also shown, to give an indication of the sun position throughout the day (with lighter colours indicating higher values). The graph at the top of the page, showing the exterior sensor reading throughout the day, was used in the analysis to identify days on which conditions were particularly stable or variable, which facilitated the study of external conditions around the times when EC window manual controls or blinds were used (see Chapter 8).



**Figure 5.8** An example of a one-day EC window control system summary sheet, from 7<sup>th</sup> November 2013

#### **5.5.4 Additional physical measurements**

The study site provided a significant opportunity to collect data on a range of aspects. Thus, in addition to the key data required to address the research questions, other relevant physical measurements, considered to carry a low overhead in terms of disruption to occupants and procurement of equipment, were included in the data collection. This additional data could be used to answer other questions that might arise in the course of data collection, or could be analysed at a later date. The additional data were as follows:

##### *(i) Weather station*

A weather station (manufactured by Delta T Devices, Ltd.) had previously been installed on the roof of a nearby university building as part of another project, and was brought into use for this study. Thus, without significant additional cost and with no additional impact upon the occupants, detailed local weather data were collected in addition to the façade illuminance and sun position information provided by the EC control system. The weather station incorporated a range of different sensors, including total and diffuse horizontal irradiance ( $\text{W/m}^2$ ), from which direct horizontal irradiance could be deduced. The sampling intervals for the irradiance sensor was set to 10 minutes, whilst for the other sensors it was set to 1 hour.

##### *(ii) Temperature measurements*

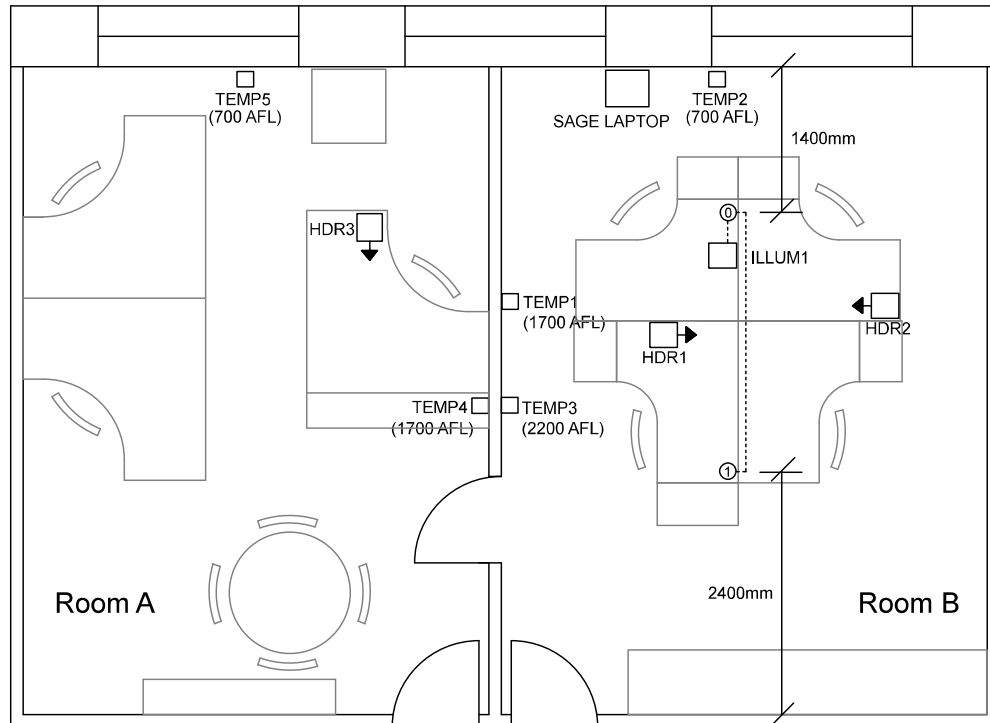
A number of small battery-powered data loggers (Onset HOB0) were available for use within the faculty. Being small and unobtrusive, a temperature logger was placed in each room to record the air temperature every 2 minutes. Additional temperature loggers were placed near heating radiators and air conditioning unit outlets to enable the status of heating and air conditioning to be monitored by recording the temperature every 30 minutes.

##### *(iii) Power consumption measurements*

Three further HOB0 loggers, coupled with current transducers, were used to monitor the current being drawn by the EC windows and lighting circuits in each room, from which the power consumption (in kW) could be deduced. These were programmed to log every 30 minutes.

### 5.5.5 Locations of physical measurement equipment

Figure 5.9 shows the locations of all the physical data collection equipment.



#### LEGEND

HDR1	MacMini ViscomC + Camera 07/0242
HDR2	MacMini ViscomA + Camera 07/0243
HDR3	MacMini ViscomE + Camera 07/0152
ILLUM1	MacMini ViscomD + Illuminance meter + 2 no. sensors
TEMP1	Hobo 1023709 (room temp)
TEMP2	Hobo 1234344 (heating)
TEMP3	Hobo 1234350 (a/c)
TEMP4	Hobo 1234353 (room temp)
TEMP5	Hobo 1248816 (heating)
TEMP6	Hobo 1248788 (a/c)

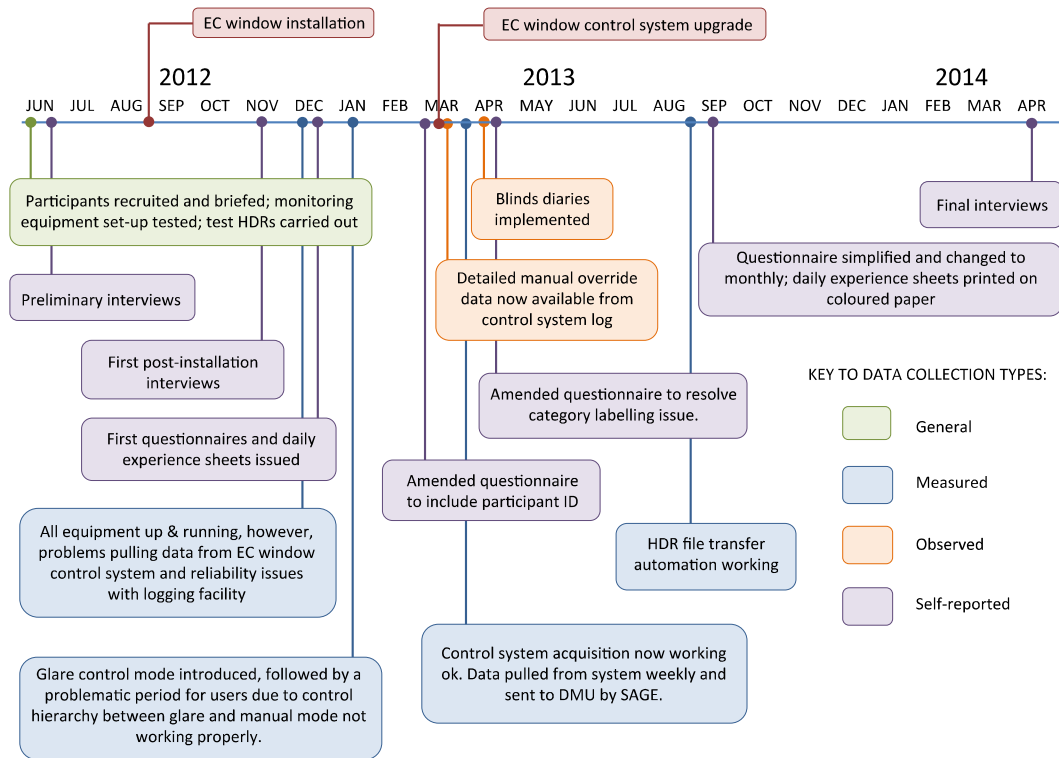
**Figure 5.9 Physical measurement monitoring equipment layout. “AFL” dimensions indicate the heights of equipment above floor level.**

## 5.6 Data collection period

The data collection needed to cover a period long enough to include a range of external conditions, *i.e.* weather and seasons). Such a period allows the consideration of longitudinal aspects that might affect occupant behaviour and attitude, such as changes in health and mood, as well as changes in the potential for visual discomfort due to varying external conditions.

The main data collection period, when all three data collection strands (measured, observed and self-reported) were running simultaneously, covered a period of 12 months, running from April 2013 to April 2014. However, the self-reported data collection and some elements of the physical monitoring commenced earlier, in late 2012. The first interviews were carried out in November 2012, and the questionnaires and daily experience record sheets commenced in December 2012. Whilst some small refinements were made to the questionnaires during the period between December 2012 and April 2013, the data collected from questionnaires during this period were still included in the analysis in order to maximise the quantity of data (given the small number of participants in the study). Therefore, the self-reported data collection spanned a period of 17 months for the interviews, and 16 months for the questionnaires and daily experience record sheets. Figure 5.10 shows the timelines of each of the three strands of the data collection.

It can be seen from Figure 5.10 that data acquisition problems meant that the collection of data from the EC window control system, including manual control usage data, did not get underway until April 2013. These issues are discussed in more depth in the next chapter.



**Figure 5.10 Data collection timelines**

## 5.7 Summary

A multi-stranded data collection programme was designed to collect information about the experience of occupants as they carried out their daily work tasks with EC windows. The data collection was shaped by the need to maximise data quality and quantity, on the one hand, and maintain participant engagement by keeping disruption to a minimum, on the other.

There were three main data streams: physical measurements of environmental parameters, observed data about occupants' behaviour with regards to their interaction with the EC window manual controls and blinds, and self-reported data from participants. This mixed data collection allows the triangulation of sources and, for some aspects, the exploration of relationships between physical conditions and subjective parameters (such as time-specific self-reported data via the questionnaires). In the next chapters, the results of the data collection and the analysis and integration of data from the different sources will be described.

## **Part III      Results**

This part of the thesis describes the outcomes of the data collection and the data analyses, and discusses meaning of the results. Though the individual chapters do not map directly to the research questions outlined in Chapter 2, the findings from each chapter are brought together in the final chapter, and structured to show more clearly how the data was used to address the research questions.

Chapter 6 is concerned with the practicalities of retrofitting electrochromic windows; Chapter 7, the results of the self-reported data collection; Chapter 8, the results of the observed data collection and Chapter 9 with the effects on occupants of electrochromic glazing tint colour. Table 2.3 (Chapter 2) illustrates how Chapters 6 – 9 relate to the research questions and can be used to aid the navigation of this part of the thesis if necessary.

The findings of all of the above chapters are brought together in Chapter 10, to form an integrated set of findings, as mentioned above. The possible factors that contributed to the results, and the implications, are discussed. This chapter also contains a critical review of the methods used to collect data, an overview of areas for further research and a final summary of the main findings.

## Chapter 6

### Installation, commissioning & refinement

When considering a refurbishment programme, the windows of buildings are often identified early as a target for improvement, since an upgrade can significantly improve the buildings' energy performance. In the UK, it is the refurbishment of existing building stock, rather than the creation of new buildings, that has the most potential for improving the energy consumption of buildings [Ma *et. al.*, 2012]. Hence, it is particularly important to learn from the retrofit application of advanced glazing materials such as EC glazing. The refinement of the control system during the months following the installation also provided a key learning opportunity. The possibilities afforded by the study to gain practical knowledge from the retrofit process and control system refinement were identified among the research questions outlined in Chapter 2.

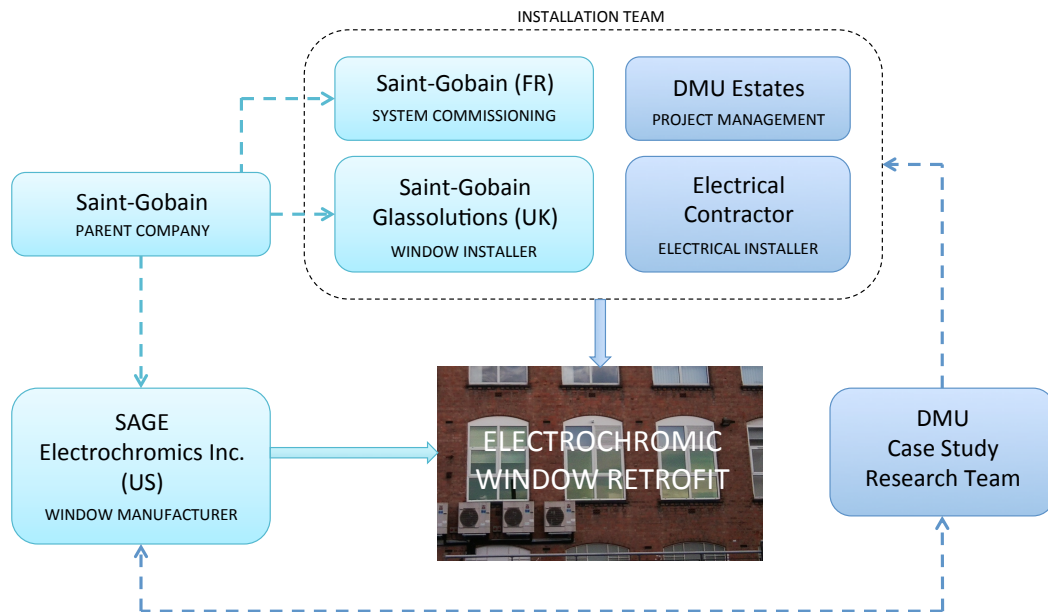
This chapter describes the events that surrounded the retrofit installation of EC glazing and the process of refining the control system during the months that followed, as recorded in the Field Diary. This examination highlights a number of practical issues, to inform future installations of EC windows, particularly in retrofit applications.

#### 6.1 EC window installation & commissioning

##### 6.1.1 Window installation

The EC window installation was a result of the joint efforts of several different parties from the university and from the window manufacturer, SAGE Electrochromics Inc., and their parent company, Saint-Gobain. The diagram in Figure 6.1 briefly explains the role of each of these organisations in the window installation.





**Figure 6.1** The EC window retrofit was a result of the co-ordinated efforts of several parties

The window installers were experienced in the installation of a range of glazing types, including advanced glazing technologies. However, they had only previously installed EC glazing once, a few weeks earlier at a private residence. However, the process of installing the windows was found to be relatively straightforward, and the physical window installation did not appear to take any longer than a traditional window replacement.

The windows were of non-standard size and had been made to order, based on measurements taken by installers some months earlier. On site, there were no apparent problems with the fitting of the window panels. It is probable that this aspect of the retrofit would entail a similar amount of risk regardless of the type of window being replaced.

### 6.1.2 Electrical connections

One of the main and obvious differences between EC windows and traditional windows is that they need electrical connections for power and communications wiring. (Although more recent versions of the product feature wireless controls

and can powered by photovoltaics, and so require less wiring.) There is also a need for the installation of control system hardware, and in this case, communications infrastructure to allow access to the control system over the internet. A further potential challenge was posed by the fact that each window contains two top-hinged opening panels.

The electrical contractors who worked on this installation had not previously been involved with fitting this type of glazing. The manufacturer provided the electrical contractor with wiring diagrams several weeks before the installation, allowing the opportunity to raise any questions or concerns before the work commenced on site. The electrical and communications wiring was completed within the same time frame as the window installation, with no obvious difficulties. The control system hardware was installed in the ceiling void of room B.

Nonetheless, an issue did arise that was caused by the installation of containment (trunking) for the window wiring. The location of the trunking in the reveal of the large window in room B (Figure 6.2) meant that the roller blind on that window could only be raised to just below the trunking, before the rigid bar along the bottom of the blind prevented it from going any further. In order to raise the blind above that point, which was over 2 m above the floor, a long pole was needed to ease the blind around the trunking. If the blind was fully retracted and an occupant later wished to lower the blind, again the pole was required in order to ease the blind back down past the trunking. In effect, this obstruction made it awkward to raise the blind completely, so occupants were more likely to leave the blind in a partially lowered position.



**Figure 6.2**

**Trunking installed in the window reveal of the large window in Room B, which obstructed the operation of the roller blind**

The problem was raised with the university estates department; however, it was not possible to relocate the trunking. Eventually, in January 2013, the roller blind was reduced in width so that it could be raised and lowered without clashing with the trunking.

The establishment of a communications link between the window control system and the internet was a key aspect of the set-up. This link would allow the window manufacturers in the US to remotely access the control system, adjust system settings and extract data as part of the data collection programme. It would also allow researchers in other parts of the campus to access the system without having to go into the study rooms. This aspect of the installation may be less relevant to future retrofit projects that do not form part of research studies. However, it is now common for clients to request such a link with the control system, to allow an interface with a building management system, for example.

The communications link took longer to establish, and may have benefitted from the same level of forward planning that was given to the power and control system wiring. For instance, the process would have been eased by the provision of a schematic diagram showing what infrastructure (*e.g.* a network connection) and hardware (*e.g.* a windows laptop) were required on site. In fact, there was some confusion over what was required, and when this was clarified and the

infrastructure and hardware were in place, the communications link could not be established at first due to the university's IT system security measures. Once this issue was resolved, the link with the window manufacturers in the US was established. During the data collection period, this connection was occasionally disrupted, usually due to network outages or planned network upgrades. Some of these interruptions were resolved by re-booting the PC, whilst others required the reassignment of the network port. This latter resolution required assistance from the IT department and took time to be completed.

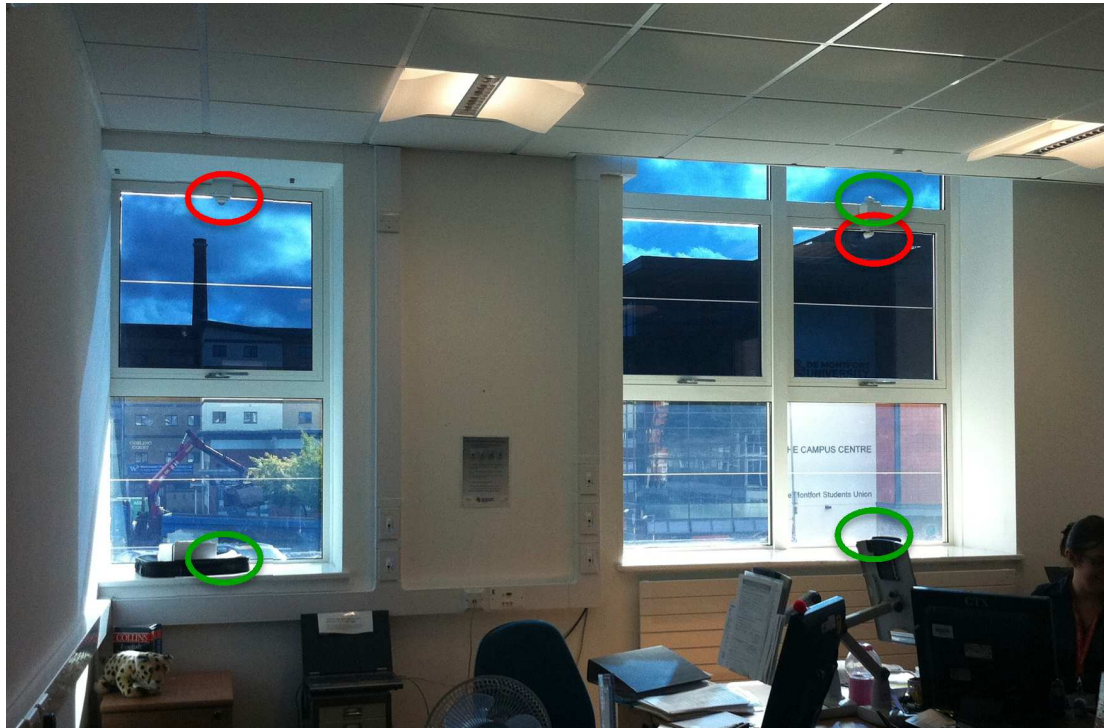
### **6.1.3 Commissioning and fault testing**

Commissioning and testing were carried out by a representative of the glazing manufacturer, who was on site during the window installation. During testing, it became apparent that one of the panes in an opening section of window in room B was not working, as it did not tint at all. It was thought that the electrochromic coating had been damaged in transit. The manufacturer was notified and a replacement was ordered. Approximately three weeks later, the replacement panel was shipped to site, but unfortunately it was the wrong size; it was for a fixed rather than opening window panel. Two weeks later, the panel was finally replaced. Further commissioning was not required, since the connections and settings remained the same. During the period before the faulty pane had been replaced, the occupants of the room pulled the roller blind on that window down so that the faulty pane was covered.

### **6.1.4 Control sensor installation**

The system was controlled by illuminance sensors mounted just inside the windows, facing out, with each zone controlled by its own sensor. The sensors were designed to be mounted horizontally, with the sensing aperture oriented towards the sky. Thus, the ideal position for a sensor would be on the windowsill, or in this case, the lowest glazing bar of the zone it controlled. However, this was not possible for zones that contained top-hinged opening panels, as the sensor would obstruct the window opening mechanism, rendering

the window un-openable. Hence, the installer mounted the sensors for these zones upside-down on the upper glazing bars, as shown in Figure 6.3.



**Figure 6.3** Illuminance sensor locations. Upside-down sensors are highlighted in red, whilst the correctly installed sensors are highlighted in green.

These sensors were effectively looking at the ground rather than the sky, and consequently the affected zones did not perform satisfactorily, as the sensors were not sensitive enough to bright, sunny conditions. The situation was improved slightly by decreasing the illuminance threshold of these zones, so that they would tint at a lower illuminance (*i.e.* increasing their sensitivity relative to the other zones). Another attempt to improve the situation was made by lowering the position of the upside-down sensors (on “stalks” – see Figure 6.4). However, the sensors were already quite obtrusive, being physically large and mounted on large back-boxes. The addition of mounting “stalks” made them more obvious and somewhat detracted from the aesthetic appeal of the new windows. Despite these measures, the poor performance of the affected zones continued, and occupants were advised to use the blinds to cover these zones when necessary until the problem was rectified.



**Figure 6.4**      **Sensor positioning**

**Left: The upside-down sensors were originally installed as shown.**

**Right: In an attempt to improve the performance of these zones, the upside-down sensors were lowered on “stalks”.**

In March 2013, the control system was upgraded to the latest available version, which resolved the upside-down sensor problem as well as a number of other issues concerning control system operation and data collection (see section 6.3). With the upgraded system, the external illuminance sensor became the control sensor for all zones, whilst still allowing zones to be controlled individually. At this point, the internal sensors became redundant, although they were left in place to avoid the labour associated with their removal.

In typical installations of EC glazing, zones were larger and thus fewer in number, and as a result the number of sensors required was kept to a minimum. In addition, previous installations with openable windows were rare, as many installations were in cooling-dominated climates, with sealed windows and air conditioning. It is likely that this scenario had not been previously encountered and hence was not anticipated.

### **6.1.5 Lighting installation**

In parallel with the EC window retrofit, the lighting in the two rooms was upgraded and a new lighting control system was installed, as described in Chapter 4. There were, however, some technical problems with the new lighting and its control system.

After the contractors had left site and the occupants moved back into their offices, participant B2 reported that the closest light fitting to her desk was too bright. She attributed the issue to her health condition, which meant she was particularly sensitive to brightness in her visual field, particularly in the peripheral area. A member of the university estates department programmed a new scene into the system so that the light fitting that was perceived as problematic was dimmed down, and the participant seemed satisfied with this arrangement. This was unexpected, because the new lighting actually provided a lower overall illuminance level than the previous system, and the light distribution of the new fittings was designed to provide light in a more diffused manner (with less peaks in brightness) than the old ones. The new luminaires were installed in the same orientation as the previous ones, to ensure that the distribution of light from the lamps were similar to that of the old system.

During the subsequent round of interviews, in November 2012, several occupants reported that the lights did not appear to be modulating in response to changing daylight levels, which suggested that daylight-linking was not functioning. They also reported episodes when some light fittings did not work at all, or when the lights dimmed down even though daylight levels were low. At times, lights switched off even though occupants were still present, suggesting that the occupancy sensor needed to be re-calibrated. Several rounds of communication between the research team and the university estates department ensued, with several visits by estates representatives attempting to rectify these issues, but without success. Eventually, in April 2013, a representative of the lighting controls manufacturer attended site. He reported that the commissioning of the system was incomplete, and that because the mains light switch was being used to switch the lights on and off, this had damaged the ballasts on some light fittings. It became apparent that the new

lighting control system should not be completely powered down using the main switch, but instead that the lighting control panel should be used for on/off control as well as dimming. Unfortunately, neither the research team nor the occupants had been made aware of this when the system was installed. Subsequently, signage was put in place instructing occupants not to use the main light switch, only the control panel. However, the damaged ballasts on some fittings could only be rectified by their replacement, and this was not possible within the budget assigned to the project.

The manufacturer's representative made some adjustments to the system, but was unable to rectify all the problems. Thus, intermittent problems with the lighting control system continued, with occasional bouts of light fittings not working, lights dimming down when ambient daylight levels were low, and lights switching off when occupants were still present.

#### **6.1.6 Other practical issues**

There were two further practical issues that arose during the first few months after the window installation:

##### *(i) Glare from window spacers*

In October 2012, participant B2 complained that the sun was glinting off the window frame, causing an intense reflection of sun that was bothersome to her. Upon investigation, it was apparent that this was as a result of the window spacers being metallic, and coupled with the small un-coated border around the edges of the panes, certain angles of sun could produce an acute specular reflection. This was reported back to the manufacturer, who suggested that masking tape be affixed to the window in the area necessary to obstruct the reflections. Masking tape was installed on the window in the affected area a few days later. Based on this experience, it is recommended that window spacers should have a non-reflective finish (*i.e.* not exposed metal) to avoid discomfort caused by specular reflections.



*(ii) Furniture obstructing window controls*

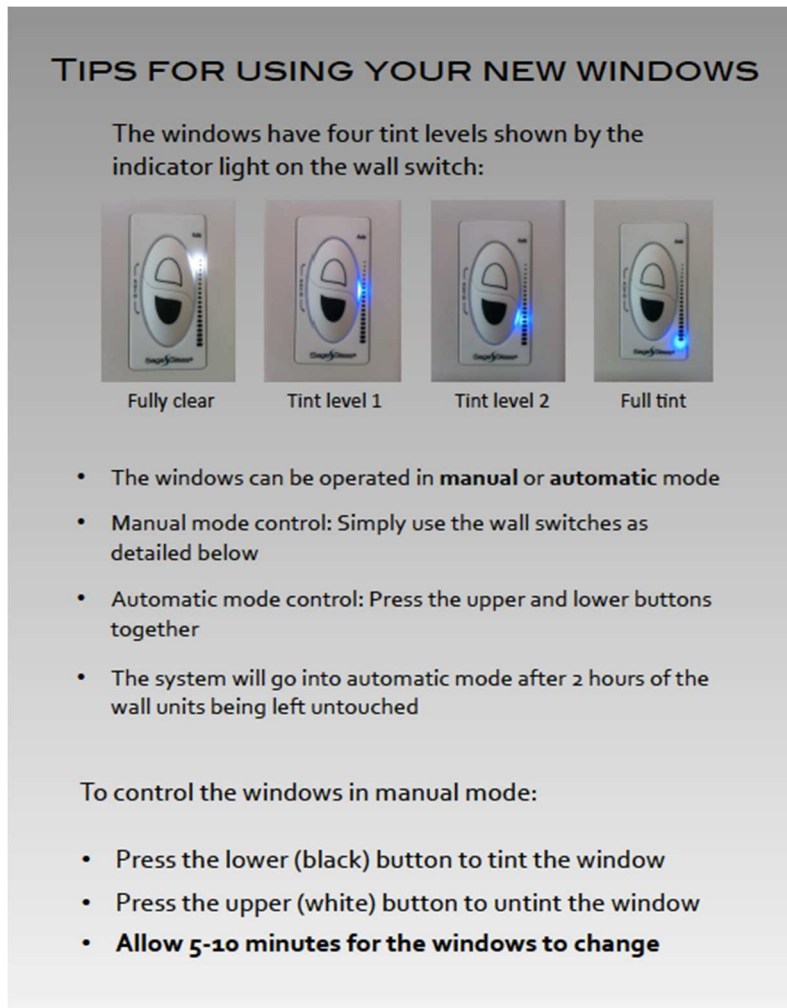
A few days after the EC window retrofit, some new furniture was installed in one of rooms, which consisted of a large cabinet around 1.5m high. It was placed in front of the window wall switches, thus obstructing them so that these zones could not be manually controlled. A request was raised to the estates department to relocate the cabinet, which took approximately two weeks. This event emphasises the need for building occupiers to be made aware of the main differences between a technology like EC windows, which many people have not seen before, and traditional windows, with which everyone is familiar.

## **6.2 Initial reactions from occupants**

### **6.2.1 The first week (3<sup>rd</sup> – 7<sup>th</sup> September 2012)**

The operation of the windows and wall switches were explained to the occupants as soon as they had moved back into their offices. A wall sign (Figure 6.5) was placed in each room adjacent to the windows to assist occupants by reminding them how to use the window controls. This approach was intended to ensure that a lack of understanding about how to use the manual controls would not be a barrier to their use.

During the first few days after the window installation, the occupants seemed positive about being back in their offices and the new windows. Later on the first day, the occupants in room B reported that they felt the new (electric) lighting was “too bright” and “giving us headaches”. A member of the estates team programmed a new lighting setting so that the light fitting nearest to participant B2, who seemed to be most affected, was partly dimmed (see 6.1.5). The occupants of room A did not appear to have any concerns about the new lighting in their room.



**Figure 6.5**      **EC window manual controls user instructions**

Later that week, two occupants in room B said that “something wasn’t quite right”, but could not be any more specific. Participant B3, who sat close to the large window with the faulty pane, said that it was rather bright if the blind was raised, but was trying to cope with lighting and blind arrangements as they were. Only one occupant was present in room A, and she said she was very happy with conditions and was enjoying familiarising herself with the window and lighting controls.

Towards the end of the first week, participant B2 raised an urgent request to have a workstation assessment, as she was still not comfortable with the new lighting conditions. This resulted in her screen being re-oriented so that she was sitting sideways to the windows, instead of at 45 degrees. The following week, she still seemed unhappy, saying that her left eye was strained (the windows

were on her left), and that she was struggling to see certain things on her screen. She thought that the problems had something to do with the colour of the EC windows when they were tinted. She said she was speaking for the others, too, in expressing a preference for the windows not being tinted. I explained that we wanted to ensure that she was comfortable, and we agreed that we would continue to monitor the situation to see how she was at different times of day and with different weather conditions, and also to reserve final judgement until the faulty pane had been replaced.

### **6.2.2 The first four months (September – December 2012)**

A few weeks on, the occupants seemed to be getting used to the new windows and lighting. A new occupant in room A (not a participant) said that she “really liked” the new windows. In room B, participant B2 said she was happier with her new desk position and the partly dimmed lighting.

In early October, the faulty pane in room B was replaced. On visiting the room, it was observed that the roller blinds were still partly lowered. It was suggested that the blind be fully retracted to “see how it goes”, now that the new pane was in and working. The blinds were retracted and the middle and top panes set to full tint. Almost immediately, participant B2 complained that it was “too much”. It seemed that the sun was glinting off the metal spacer between the panes of glass (see 6.2.6). Participant B2 said that she would like the blind to be lowered “back where it was”, and this was duly done. During a visit later that day, the blinds appeared to have been lowered further. The participant near the large window, B3, said she had done it because the sun was on her screen. When asked why she hadn’t manually tinted the windows instead, she said that the windows were already tinted and that it wasn’t enough. However, it is likely that the middle zone was not fully tinted due to the problems with the sensors in that zone (see 6.2.4).

In a conversation with occupants of room B about what visitors seemed to think of the new windows, one occupant (participant B3) said that a few people had asked things like “why is it so gloomy in here?” However, another occupant (not

a participant) said that one visitor had commented on how bright the room seemed. In room B, the blinds on the large window continued to be used regularly. Later in October and at various points in November, the occupants of room B said that they were unhappy with the response time of the glazing, especially when the sun came out from behind cloud. On a clear day in December 2012, sitting at participant B2's desk with the blinds fully retracted, it was observed by the researcher that the sun orb was visible in the window and it was uncomfortably bright, even with the glazing fully tinted.

The occupants of Room A seemed happier with the windows in general. As the sun altitude became lower in December, they said they would use the blinds if necessary, but it was notable that they had not used them up to that point.

### **6.3 Control system refinement**

Once installed, the EC windows operated using the default system settings. Whilst these settings were a good starting point, they needed to be adjusted to suit the needs of the site and occupants. The goal of refining the control system was to optimise EC window performance and maximise user satisfaction with the system by adjusting control system set-points to more closely anticipate the needs of users. It is, of course, possible that the control system could be optimised from the point of view of users but behave sub-optimally from the point of view of energy consumption. However, in order to measure this, it would be necessary to embark on the full-scale measurement of energy consumption of lighting, heating, and cooling systems, which was not within the scope of the study. Hence, control system refinement was primarily aimed at maximising user satisfaction.

Refining the control system was an iterative process of adjustment in response to feedback from the users and direct observation. This feedback was obtained during researcher visits in the period following EC window installation and via interviews with participants. The process was complicated by problems with control system data acquisition, an issue that persisted until the control system was upgraded to the latest available version in March 2013. The difficulty in

obtaining robust system data made it difficult to test the effect of new settings on control system behaviour. Thus, occupant feedback became the most important tool in this process.

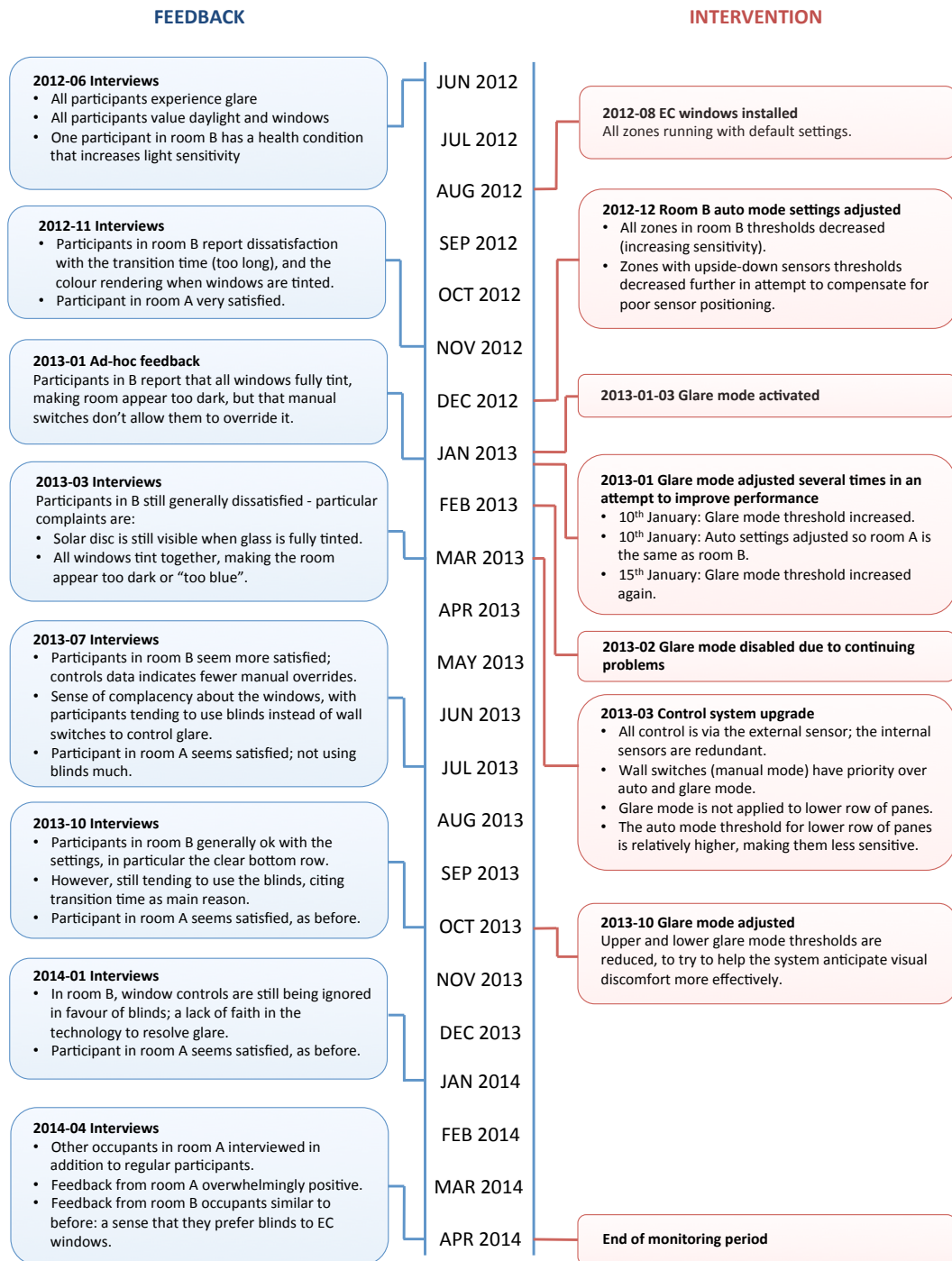
Figure 6.6 summarises the control system refinement process in the form of a timeline of user feedback and control system adjustments. In the sections that follow, these adjustments will be explained in more detail. Table 6.1 provides an overview of the control system settings at different stages during the months following the EC window installation and into the data collection period.

### **6.3.1 Initial adjustments: December 2012**

The first set of adjustments was made in December 2012 to the zones in room B only. The purpose was to see if lowering the thresholds of all zones would make the windows more responsive and improve the perception of room B's occupants. The zones with the upside-down sensors (Zone 5 and 8) were assigned relatively lower thresholds in an attempt to counteract the problems with these sensors, as explained previously.

### **6.3.2 Glare mode: January-February 2013**

Feedback from occupants in room B, both from ad-hoc conversations and from the November 2012 interviews, indicated that they felt the windows were too slow to respond. This prompted the manufacturer to add glare mode to the system in early January 2013, as it had not yet been activated. It was considered that glare mode might enable the system to be better at anticipating the needs of occupants so that they would be less aware of the transition time.



**Figure 6.6** Timeline of control system refinement

**Table 6.1** EC window control system setting adjustments. U = Upper sensor threshold (klux), L = Lower sensor threshold (klux)  
The shaded columns indicate settings that were in place during the main data collection period (April 2013 – April 2014)

Zone	30 August 2012		05 December 2012		03 January 2013		10 January 2013		15 January 2013		28 February 2013		23 March 2013		26 October 2013	
	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L
1	12	3	12	3	12	3	2	0.5	2	0.5	2	0.5	5	1.25	5	1.25
2	12	3	12	3	12	3	6	1.5	6	1.5	6	1.5	26	6.5	26	6.5
3	12	3	12	3	12	3	2	0.5	2	0.5	2	0.5	5	1.25	5	1.25
4	12	3	12	3	12	3	6	1.5	6	1.5	6	1.5	26	6.5	26	6.5
5	12	3	2	0.5	2	0.5	2	0.5	2	0.5	2	0.5	5	1.25	5	1.25
6	12	3	3.6	0.9	3.6	0.9	6	1.5	6	1.5	6	1.5	26	6.5	26	6.5
7	12	3	3.6	0.9	3.6	0.9	6	1.5	6	1.5	6	1.5	5	1.25	5	1.25
8	12	3	2	0.5	2	0.5	2	0.5	2	0.5	2	0.5	5	1.25	5	1.25
9	12	3	3.6	0.9	3.6	0.9	6	1.5	6	1.5	6	1.5	26	6.5	26	6.5
Glare mode	N/A	N/A	N/A	N/A	3	1.7	6	1.5	10	3.9	N/A	N/A	30*	25*	21*	10*

\* Glare mode was not applied to the lower pane zones (2, 4, 6 & 9)

As explained in Chapter 5, the upper threshold of a zone is the sensor reading above which the glazing in that zone would be tinted to the next lowest available transmittance. Similarly, the lower threshold is the sensor reading below which the glazing would be un-tinted to the next highest available transmittance.

Following glare mode activation, occupants in room B reported that the windows seemed to tint too quickly and too fully, often when they felt that it was unwarranted. In response to this, the glare mode upper threshold was increased, in order to make it less sensitive. However, occupants in room B were still not satisfied, and the glare mode threshold was increased again a few days later. Occupants then reported that when they tried to manually override the windows, the switches didn't work and the windows remained fully tinted, causing frustration and annoyance. The problem was reported to the manufacturer, who confirmed that there was an error with control priority, *i.e.* that glare mode was taking priority over auto and manual mode, when manual mode should have had the highest priority.

During February 2013, clear patches appeared in the electrochromic coating of the large window in room B. The problem was reported to the manufacturer, who suggested that this might be a result of the rapid cycling of the windows when occupants frequently attempted to override glare mode using the wall switches. The patches did not persist, however, the episode may have further reinforced the poor opinion of the windows held by some of the occupants of that room. It was eventually agreed to disable glare mode at the end of February 2013.

### **6.3.3 Control system upgrade: March 2013**

The manufacturer proposed an upgrade to the latest available control system, with the aim of resolving a number of issues:

- Sensors: All control would now be via the external façade sensor, thus removing the problem of the upside-down interior sensors.
- Manual mode priority: The problem of control mode priority would be fixed, so that manual mode would have priority over auto and glare mode.
- Data acquisition: The new control system would provide all logged information in one spreadsheet, which would be provided by the manufacturer on a monthly basis.



The upgrade was carried out in March 2013 and overseen by a representative of the EC window manufacturer who attended site.

Feedback from occupants in room B indicated that they felt that when the windows were tinted, the room appeared “too dark” or “blue”. In response to this, further changes were made to the control system settings once the new control system was in place. The lower zones (2, 4, 6 & 9) were given higher upper thresholds, to make them less sensitive than the upper zones. Glare mode was re-activated, but only assigned to the upper zones so that the lower row of panes would tint less often.

In consultation with the manufacturer, a further adjustment was made to the glare mode settings in October 2013. The upper glare mode threshold was decreased to trigger glare mode at a lower façade illuminance, and the lower threshold was also decreased, so that the system would remain in glare mode for longer.

## **6.4 Discussion**

This EC glazing installation was the first of its kind in the UK, and thus represents a significant learning opportunity. There are a number of findings that can be drawn from the experience. Some are practical and relate to the installation process itself, whilst others are more wide-ranging and relate to the suitability of EC glazing in different applications.

### **6.4.1 Occupants’ impressions following the retrofit**

In the period following the EC window installation, a clear division in attitude became apparent between the two rooms, with the occupants of room A seeming largely satisfied and the occupants of room B seeming largely dissatisfied.

One possible reason for this is that room B was disproportionately affected by technical problems with the windows. It is highly likely that the presence of a faulty glazing pane in room B irrevocably damaged occupants’ trust in the technology. The faulty pane remained in place for a number of weeks, during

which occupants had to use the blind to cover it. When the faulty pane was replaced, however, the occupants seemed reluctant to stop using the blind, citing a number of different reasons. It is likely that a negative impression of the EC windows had become established. The various other technical issues, such as the poor sensor positioning and the clash between trunking and blinds, only served to exacerbate this. In room A, the blinds were fully retracted when the occupants moved back into their office after the EC window installation. They seemed to accept this “new reality” more readily than their neighbours, and did not appear use the blinds until the sun altitude became very low in December. However, it is likely that differences in the room layouts and seating positions were also at play; this is discussed in section 6.4.3.

There were a number of technical problems with the operation of the lighting control system. In addition, occupants in room B appeared generally dissatisfied with the new lighting, with participant B2 in particular finding the new light fittings too bright, despite the new lighting delivering a lower illuminance and having more diffused optical control than the previous lighting. Evidently, perception of lighting conditions is a function of many factors besides quantitatively measured illuminance and luminance levels. Even though the lighting system was separate from the EC window system, from the occupants’ point of view, the two systems are likely to have been strongly associated. Thus, it is possible that the dissatisfaction with the new lighting in room B contributed to dissatisfaction with the EC windows.

#### **6.4.2 Control zones**

The process of refining the control system settings highlighted both the importance of being able to change the settings after installation and the benefit of the flexibility afforded by the zoning of the windows. The first attempt at adding glare mode to the system in January 2013 illustrated this, when it was found that occupants did not like the affect produced when all zones were fully tinted. Thus, after the control system upgrade in March 2013, the upper and lower zones were assigned different thresholds, so that the lower zones remained un-tinted for more of the time. It was considered that occupants would

value having an “un-filtered” view out (through the lower panes) more of the time, and that they would be more satisfied with the overall effect that resulted from having a mixture of tint levels across the zones. Data collected in the questionnaires and interviews indicate that this strategy was largely successful. This will be discussed in more detail in Chapter 7.

### **6.4.3 Room layout**

A key finding concerns the layout of the rooms. In early December 2012, the first winter after the window installation, observations indicated that when the sun was visible through the glass, the fully tinted state was not enough to reduce its brightness to a comfortable level. The brightness of the solar disc is of the order of  $10^9$  Cd/m<sup>2</sup>, so it is not surprising that even at a minimum tint level of 2%, some users may still find it uncomfortable to view the sun directly. At the time of writing, the latest available version of the glazing has a minimum transmittance of 1%. However, it is possible that even at this lower transmittance, some observers would still find direct views of the sun uncomfortable. The question this raises is one of expectation; is it reasonable to expect a glazing material such as this to adequately control glare without the need for blinds?

Notwithstanding the effects of façade orientation and the needs of individual occupants, the answer largely depends on the function of the space in which the glazing is installed. If it is an office, as in this case, where occupants are seated in relatively fixed positions for extended periods of time, then the layout should be given serious consideration if the need for blinds is to be minimised. If direct views of the sun are possible from any workstations, these should be reviewed and modified where possible. In addition, workstation orientation should be easy to modify, given that occupants’ tolerance of glare from daylight is likely to be increased if they can change their position [Jakubiec & Reinhart, 2012]. In this case, a retrofit, it was considered that the occupants had endured enough upheaval without the room layout also being changed. With hindsight, more attention would have been given to this aspect, by agreeing on a new layout in consultation with the occupants and re-arranging the furniture before they re-occupied the rooms. This process would potentially have been time intensive,

but arguably worth the effort. However, it is not possible to know whether a revised layout would have counteracted the effect of the technical problems with the windows, such as the faulty glazing pane in room B and the poor sensor positioning in some of the zones. The importance of room layout also emerged from the longitudinal data analysis, and will be discussed in more depth in Chapter 10.

## 6.5 Summary

The EC glazing retrofit at the centre of this study has raised a number of practical issues. Even with careful planning, it is not always possible to avoid problems in an installation such as this, however, it is hoped that some of the problems that arose from this process have provided a learning opportunity and thus can be avoided by future installations of EC glazing, particularly retrofits.

Based on the experience gained from this installation, a number of recommendations can be made for early adopters of EC glazing. These recommendations are grouped according to each stage of the process: Prior to installation, during installation, and after installation.

### *Prior to installation:*

- The glazing manufacturer should provide a detailed specification of the windows and control system for the client, including a list of hardware that will be installed as part of the system (*e.g.* sensors, wiring, control system hardware, communications link hardware).
- The glazing manufacturer should provide detailed wiring diagrams, system specifications, layouts of cabling routes and containment sizes, particularly for the benefit of electrical contractors.
- The locations of items such as wall switches, sensors, containment and control hardware should be agreed with the client in advance of the installation.

- If resources allow, windows and hardware should be shipped to site in advance so that they can be connected and checked to see that they are functioning properly prior to window installation. This could avoid the inadvertent installation of malfunctioning parts.
- Adequate consideration should be given to the electric lighting system. If a daylight-linked system is not already in place, the lighting should be upgraded to a fully dimmable daylight-linked system, to take full advantage of the potential energy savings brought by the installation of EC windows. The lighting system should be installed and commissioned with as much input from the manufacturer as possible, preferably with their direct involvement on site. Furthermore, all users of the system should be fully briefed to ensure that they know how to operate the system and know how to access the system literature if required.

*During installation:*

- A representative of the glazing manufacturer should be contactable during the entire installation.
- The client or client's representative should attend site to check that equipment is installed in the agreed locations, and to agree new locations if changes are required.

*After installation:*

- Building owners and occupants should be fully briefed to ensure that they know how to operate the manual controls and how to access the system literature if required.
- Building owners and occupants should be briefed to ensure that post-installation changes (such as the introduction of new furniture or equipment) do not hinder the proper functioning of the windows or access to the manual controls.
- On-going remote access to the control system is recommended so that system settings can continue to be adjusted by the window manufacturer or the client. This ensures optimal performance throughout the seasons

and in response to changes to the building, such as changes of use or personnel. If a communications link is to be included, clear communication and briefing of the local IT staff is recommended. This should include a schematic diagram indicating hardware, software and communications infrastructure required at the site.

In addition to the above recommendations, the post-installation experience indicates that consideration should be given to the existing furniture layout, and this is particularly important in a retrofit, where an existing layout may already be established. To improve user acceptance, the layout should be changed if necessary to avoid direct views of the sun whilst seated in the normal working position.

The process of refining the control system indicated that zoning was a valuable feature, so it is recommended that, where possible, and particularly for large glazed areas, glazing should be divided into a number of control zones to allow maximum flexibility with control settings. The last changes to the control system were made in October 2013, almost 14 months after installation and seven months after the control system upgrade. In this study, the duration of control system refinement was prolonged due to the data acquisition problem among others, however this experience suggests that a period of at least six months should be allowed for settling-in and control system adjustment. A six-month period is also beneficial because it includes a comprehensive range of sun positions and weather conditions. It is also noted that a summer installation, such as the one in this study, provides the opportunity for occupants to become familiar with the technology for a few months under less challenging conditions before the sun altitude decreases in winter.

With an increase in the number of installations of advanced glazing systems such as EC glazing across the UK and Europe, it is anticipated that installation teams will become more familiar with the process, thus reducing the risk of unforeseen complications. Furthermore, knowledge about control system settings and set-ups used in similar locations could help avoid a prolonged period of control system tuning.

## **Chapter 7**

### **The user perspective**

This chapter describes the self-reported data, comprised of the daily experience record sheets, questionnaires and interviews, which were collected during the period November 2012 – April 2014. The quantitative questionnaire data were analysed in combination with measured data from other sources, in order to explore the relationship between perceived and measured lighting conditions.

The self reported data offer a direct insight into the experience of working in an office whose windows are glazed with EC glass over a longitudinal period. The information gathered covers a wide range of topics, as described in Chapter 5, including satisfaction with lighting conditions, frequency and severity of visual discomfort, and satisfaction with the EC window control interface. Thus, the data address a number of the research questions identified in Chapter 2: those concerned with visual comfort as well as the user experience of the controls interface and settings. Thus, these data are of central importance to the study, as they provide an underlying narrative that gives context to data from other sources.

#### **7.1 Daily experience record results**

Daily experience sheets were given to participants monthly during the period December 2012 to April 2014 (17 months). When completed, the sheets provided a useful overview of each participant's experience of the EC windows. Typically, participants used the spaces provided to add comments as well as highlighting the relevant icon to indicate their satisfaction on a given day, as shown in the example in Figure 7.1. In preparation for analysis, the happy/neutral/sad responses were coded and entered into a spreadsheet, together with any comments added by participants. In this way, this source provided both quantitative and qualitative data.

How were the windows for you today?  
Please circle the appropriate icon.

Name:

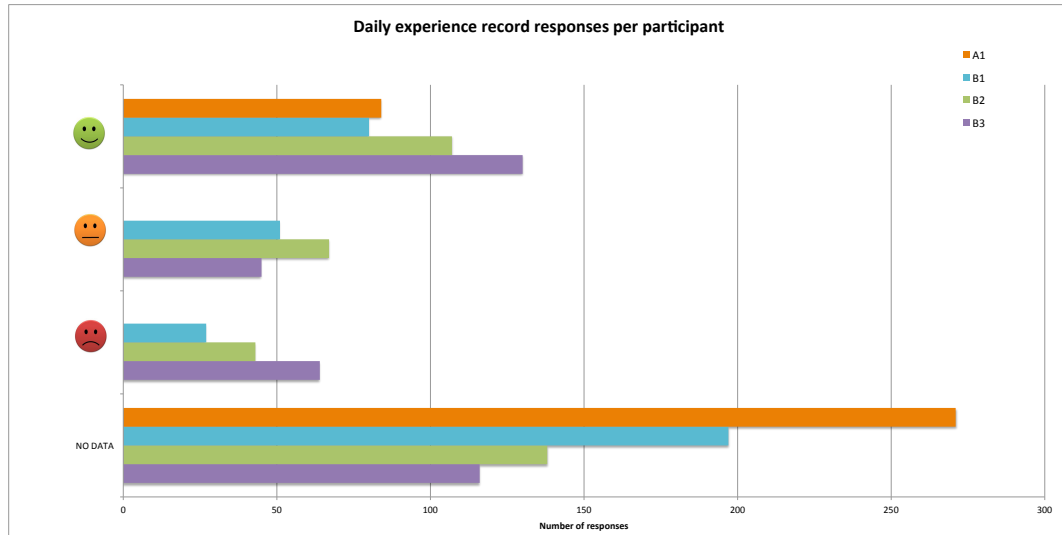
Week commencing	Monday	Tuesday	Wednesday	Thursday	Friday
4 Feb 2013	 Comment: NOT HERE	 Comment: NOT HERE	 Comment: Really heating cooly. Dark window should be higher and use more	 Comment: Same problems	 Comment: Same again!
11 Feb 2013	 Comment: no visible problems today.	 Comment: Fine	 Comment: Fine	 Comment: Fine	 Comment: Having the win- dow with them today!
18 Feb 2013	 Comment: Temp/pressure again - Sun still comes through window	 Comment: No problems	 Comment: No problems	 Comment: No problems	 Comment: No problems
25 Feb 2013	 Comment: No problems	 Comment: No problems	 Comment: Good day today - no problems	 Comment: No problems	 Comment: NOT HERE

**Figure 7.1** Example of a completed daily experience sheet, from participant B2 in February 2013

### 7.1.1 Quantitative data

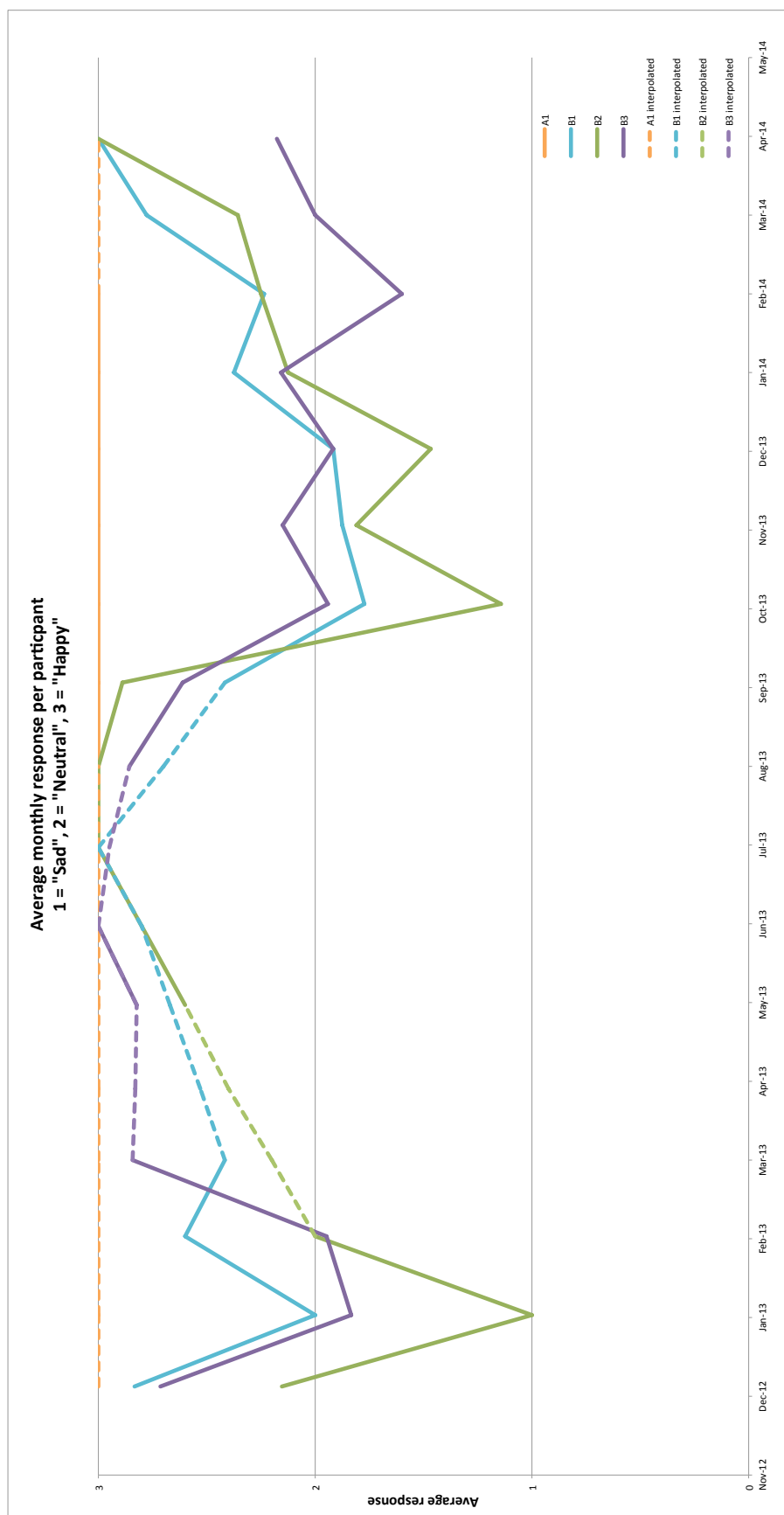
Figure 7.2 shows a summary of the number of daily responses in each category from each participant, including “blanks”, *i.e.* when no data were provided. Some months, sheets were returned that were either completely blank or had some days for which no response had been given, either due to the participant not being at work that day or simply because they had forgotten to fill it in. It can be seen that there were a relatively large number of “no data” days. This was a particular problem with participant A1, who provided a total of seven completed sheets out of a possible 17. When initially asked about her low response rate, participant A1 indicated that she was generally very happy with the EC windows, and thus had no further comments to add. When she did provide completed sheets (during August 2013 – February 2014), all her responses were in the “happy” category. For the other three participants, whilst the “happy” category has the highest number of responses (other than “blanks”), there are also large numbers of responses in the “neutral” and “sad” categories.





**Figure 7.2 Summary of daily experience sheet responses from each participant**

Figure 7.3 shows how participants' responses varied over time, based on the average response per month for each participant. It can be seen that, with the exception of participant A1, there was a noticeable dip in satisfaction levels in January 2013 and October 2013. The first of these coincides with glare mode problems, and the second occurred at a time when there were numerous issues with the lighting system (both of which are described in Chapter 6). As evidenced by the interview data (section 7.3), participants' attitudes towards the EC windows and lighting system were closely associated and it is thus likely that participants' satisfaction with the lighting influenced their satisfaction with the EC windows. It can also be seen that there is no data during the summer months of 2013. However, the data that were obtained on either side of this gap suggests that satisfaction was generally higher during the summer months. This is expected due to higher solar altitude during this period, resulting in less direct solar penetration in the rooms.



**Figure 7.3 Monthly average daily experience sheet response for each participant.**  
 For months with no data, points have been linearly interpolated between the data points either side, as represented by the dashed lines on the graph. Whilst these data points are speculative, they enable the trends in the graph to be more clearly seen.

### 7.1.2 Qualitative data

Participants in room B often used the daily experience sheets to provide additional comments about their experience. (Participant A1 did not provide any additional comments.) These comments became a key feedback tool, and also enabled results to be interpreted more easily during analysis. It is particularly instructive to look at the comments made during months with noticeably lower average satisfaction levels. Table 7.1 shows the comments made by participants during January 2013. Note that only dates with comments are included in the table. “N/C” indicates that no additional comment was made.

The comments show a palpable sense of frustration at the behaviour of the EC window control system, particularly from participant B3. Thus, satisfaction scores during this month can be strongly linked to the performance of the glazing in glare mode.

**Table 7.1 Daily experience sheet comments from January 2013**

Date	B1	B2	B3
07/01/2013	Windows suddenly went dark even though not sunny.	Windows really dark although no sunshine?	Windows went dark although cloudy outside.
08/01/2013	N/C	N/C	As yesterday. Not working on auto.
09/01/2013	N/C	N/C	As yesterday.
10/01/2013	N/C	N/C	Similar to Monday but slightly better.
11/01/2013	N/C	N/C	Windows too sensitive and going dark too quickly.
16/01/2013	N/C	N/C	As yesterday.
17/01/2013	N/C	N/C	As yesterday.
18/01/2013	N/C	N/C	Cloudy day (snow), didn't need to darken windows.
21/01/2013	N/C	N/C	Cloudy, no need to darken windows.
28/01/2013	N/C	N/C	Windows misbehaved a little.
29/01/2013	N/C	N/C	Windows misbehaved.
30/01/2013	N/C	N/C	Windows misbehaved.
31/01/2013	N/C	N/C	Keep having to switch the window, which doesn't respond to my changes either.

Similarly, it is useful to look at the comments provided during October 2013 (Table 7.2). It can be seen that many of the comments were to do with the lighting system, indicating that the lights regularly dimmed unexpectedly. A number of comments were also made about glare on computer screens, primarily from participant B1 and B3, whose screens are tangential to the window wall (see Figure 7.13). A comment from participant B1 on the 23<sup>rd</sup> October indicated that the EC window control system was not behaving as expected, *i.e.* with the window apparently tinting when conditions were dull and un-tinting when conditions were bright. It is possible that weather conditions that day were such that façade illuminance was fluctuating, and this was confirmed by looking at the façade illuminance profile for this date (not shown here). Nonetheless, the number of comments that relate to the lighting system during this period strongly indicates that the low satisfaction scores in this month were mainly attributable to lighting problems.

**Table 7.2 Daily experience sheet comments from October 2013**

Date	B1	B2	B3
02/10/2013	Lighting levels have been too dark - had to switch off and on again	Lights in office kept dipping	Lighting fluctuates
03/10/2013	See Wednesday comment	Same again	Lighting fluctuates
04/10/2013	See Wednesday comment	Lights keep dipping	Glare on screen at 11.50
08/10/2013	Glare on screen	Sun on screen first thing	Glare on screen around midday, pulled blind
09/10/2013	Glare on screen	Lights keep dipping!	Glare on screen 9.15 - pulled blind
10/10/2013	Reflections on screen - had to use blind	Lights keep dipping!	Glare on screen 1.10 - pulled blind
11/10/2013	N/C	Lights keep dipping!	N/C
14/10/2013	Lighting controls playing up	Lights again!	N/C
15/10/2013	Reflections on screen	Lights keep dipping!	Issues with lighting dipping also glare on screen at 1pm.
16/10/2013	N/C	Lights keep dipping!	Lighting fluctuating
17/10/2013	Reflections on screen	Lights keep dipping!	Although bright the office appears quite dull, put lights on
18/10/2013	Lighting controls playing up	Lights keep dipping!	Lights fluctuating, grey day

Date	B1	B2	B3
21/10/2013	Lighting levels playing up	Hardly any lighting all day	Even though lights are on, office quite dull. Suddenly lit up at 10.30 am.
22/10/2013	Lighting levels playing up	Lights keep dipping!	Light ok 8.30am
23/10/2013	Windows going dark when they don't need to and not turning dark when required so used blind	Lights keep dipping!	N/C
24/10/2013		Lights keep dipping!	N/C
25/10/2013	Lighting levels too dark - can't even see my keyboard!	N/C	N/C
28/10/2013	Lighting levels temperamental	Lights adjusted in my absence, now can't work as too bright!	Lighting levels temperamental
29/10/2013	N/C	Lights!	Lights on dim even though bright. Middle windows tinted, lower un-tinted.
30/10/2013	N/C	Lights!	N/C

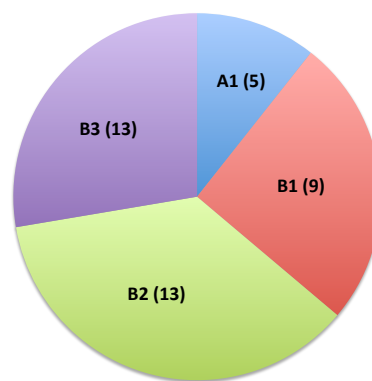
### 7.1.3 Summary

The quantitative data gathered using the daily experience record sheets enable a broad pattern to be detected over the data collection period. The data suggest that satisfaction with EC glazing was generally higher in summer than in winter, corresponding to lower sun altitude in winter and thus a higher likelihood of glare. Furthermore, it is apparent from the qualitative data (additional comments) that occupants' experiences of the lighting system influenced their reported satisfaction with the EC glazing.

## 7.2 Questionnaire results

### 7.2.1 Overview

Participants completed a total of 47 questionnaires during the study. The vast majority of responses were from occupants of room B, mainly because three of the four participants were from that room, but also because participant A1 failed to complete a number of questionnaires (though her response rate later increased). Only 10% of responses came from participant A1. Figure 7.4 illustrates the number of completed questionnaire per participant.



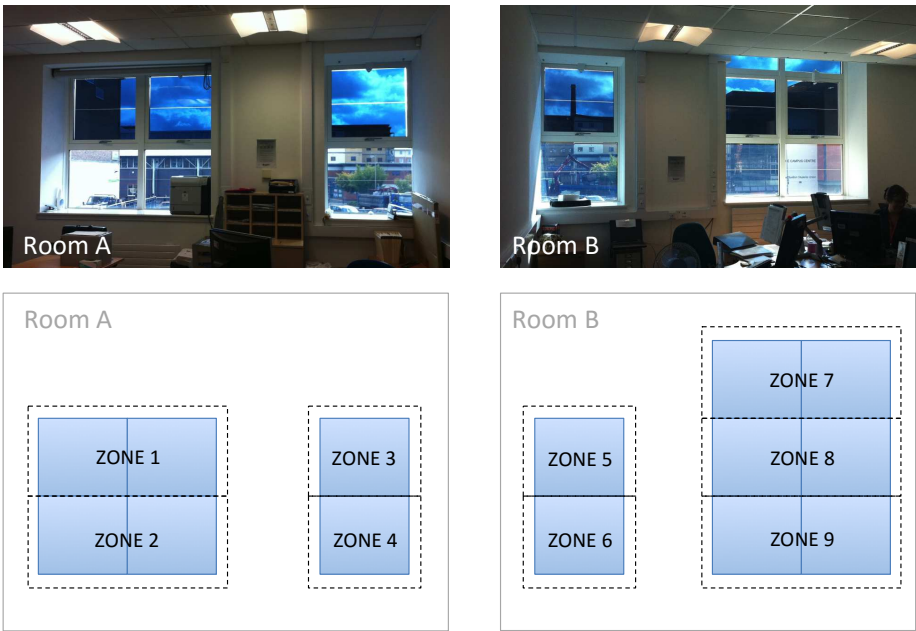
**Figure 7.4** Number of completed questionnaires from each participant

The questionnaire was designed to enable participants' responses to be linked to physical conditions at the time. With the exception of the final question, participants were asked to respond to each question in terms of how they felt at that moment. They were allowed to answer the questionnaire at a time convenient to them within a specified two-week period, as long as it was during daylight hours. The time of response was not dictated because it was not considered reasonable to expect participants to be able to interrupt their work tasks in order to complete the questionnaire.

Considering that the main aim of the questionnaire was to find out about the effect of the EC windows on participants, it is judicious to examine the transmittance state of the EC windows at the times when questionnaires were completed (*i.e.* within a minute of the questionnaire time stamp). The first seven questionnaires were completed before the EC window control system upgrade in

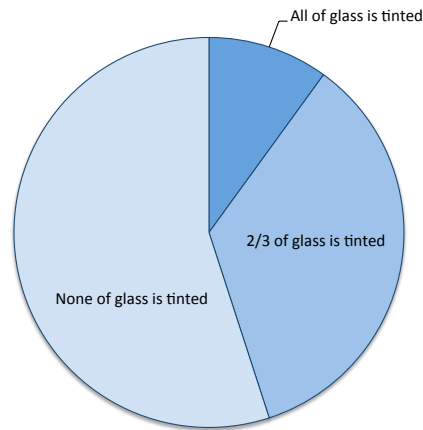
March 2013, and thus there are no corresponding control system data for these. For the remaining 40 questionnaires, the transmittance state of each window control zone at the time could be identified.

As described in Chapter 4, the windows were divided into 4 zones in room A and 5 in room B. For clarity, this information is illustrated again in Figure 7.5. The control system was set up so that the upper zones (1, 3, 5, 7 & 8) were more sensitive the lower zones (2, 4, 6 & 9). In practice, this meant that under moderately bright conditions, the upper zones were typically tinted to some degree whilst the lower zones remained un-tinted.

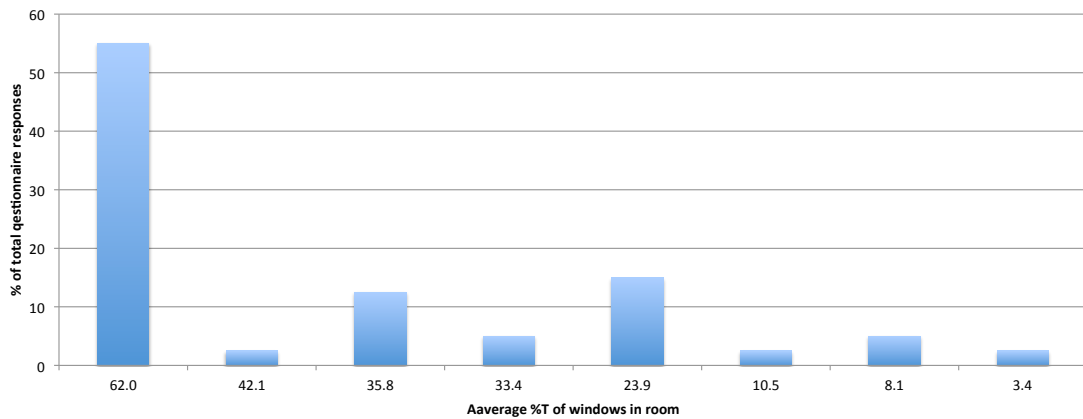


**Figure 7.5 Window control zones (repeated from Chapter 4)**

Thus, when the transmittance of window zones at the times of questionnaire response was examined, they typically fell into a small number of categories. In Figure 7.6, the tint state of all the zones at the time of questionnaire response is summarised by giving the proportion of glass in the room that was tinted to some degree. The degree of tint is shown in Figure 7.7, which shows the area-weighted average transmittance of glazing in the participant’s room at the time when they responded to the questionnaire.



**Figure 7.6** Proportion of glazing that was tinted at questionnaire response times



**Figure 7.7** Area-weighted average transmittance (%T) of windows in respondent's room at time of questionnaire response

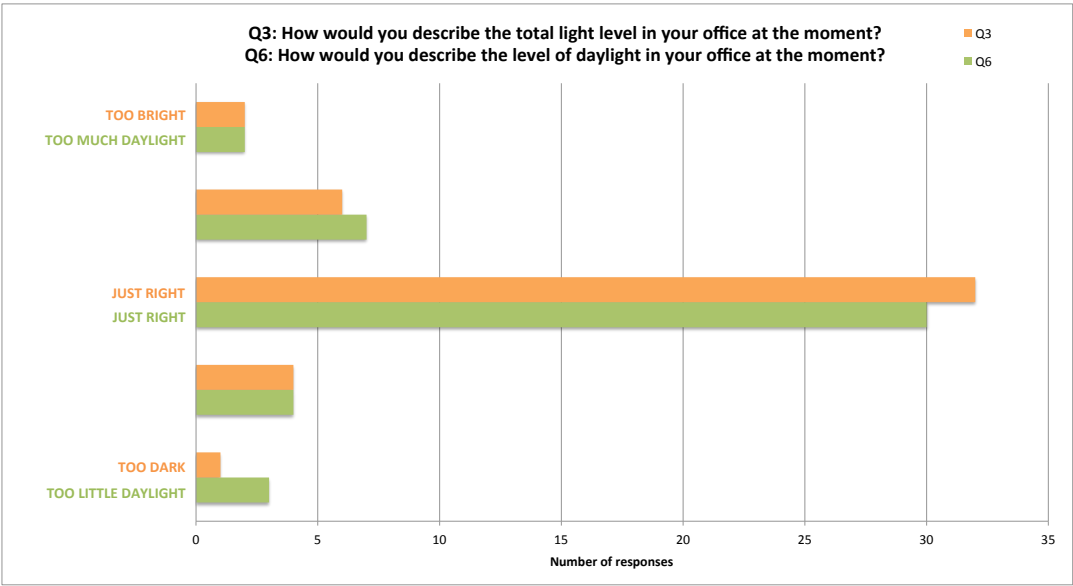
It can be seen that questionnaires completed at times when the windows were tinted (to some degree) account for less than half of all the analysable questionnaire data. In addition, the blinds were used frequently in room B, so that the effect of the EC glazing tint state alone cannot be isolated. Thus, given that participants from room B account for the majority of questionnaire responses, it is unlikely that their responses can be directly linked to the condition of the EC windows at the time. Essentially, this means that there is a limit to how much these responses can be used to quantify, specifically, the effect of the EC glazing tint on various subjective parameters. Nonetheless, the data



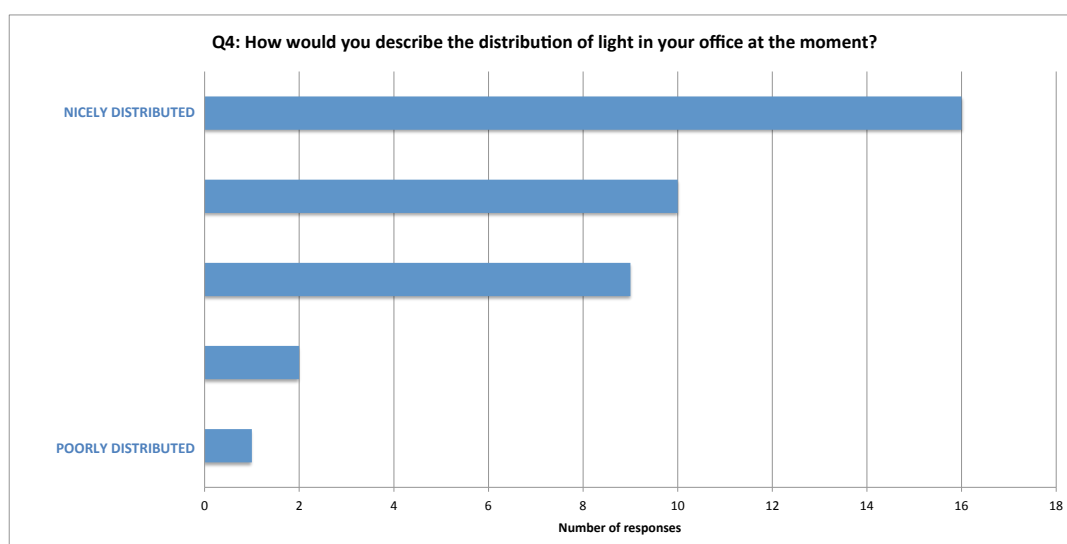
were analysed as part of the systematic process of investigating possible relationships between these parameters.

**7.2.2 Perceived lighting conditions (Q 3 – 6)**

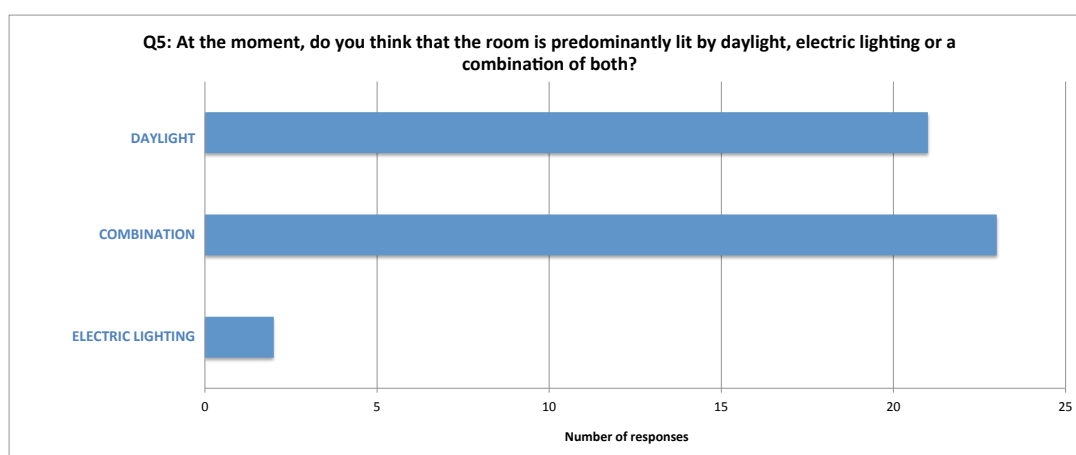
The first four questionnaire items relate to the participants’ perception of lighting conditions in the room. The results are shown in Figure 7.8, 7.9 and 7.10. They suggest that, in most cases, participants were happy with lighting levels (Figure 7.8) and the distribution of light in the room (Figure 7.9). For the perceived dominant source of light in the room, half of the responses indicated that it was a combination of daylight and electric light, whilst almost half considered daylight to be the dominant source (Figure 7.10).



**Figure 7.8** Perceived total light level and daylight level (responses to Q 3 & 6)



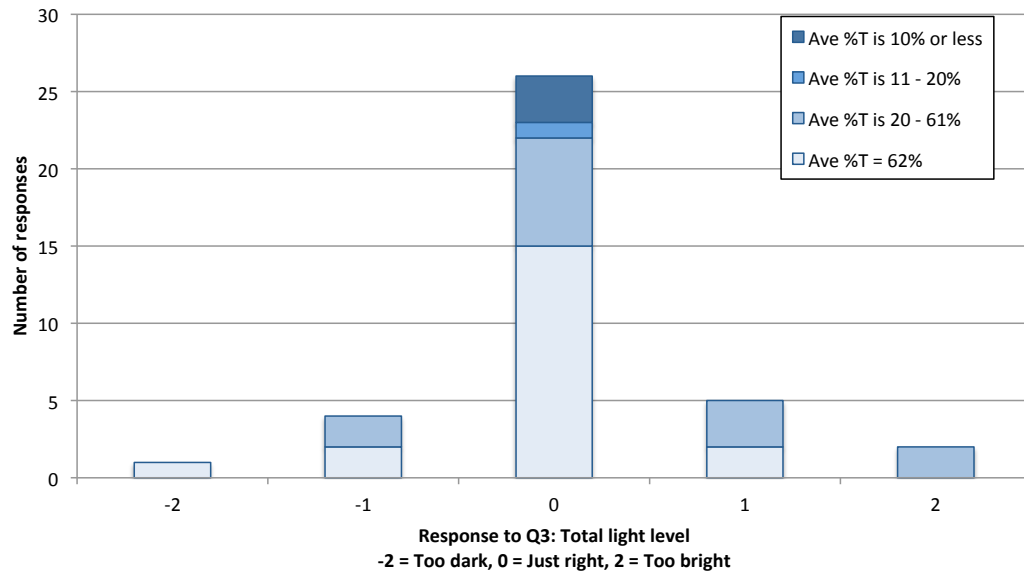
**Figure 7.9 Perceived distribution of light (response to Q4)**



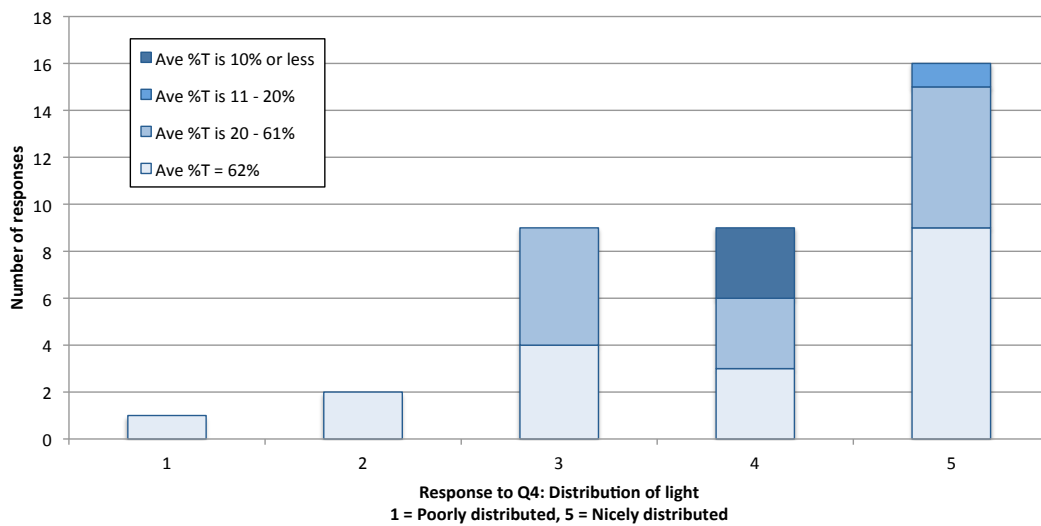
**Figure 7.10 Perceived dominance of daylight (responses to Q5)**

### *EC window conditions at times of response*

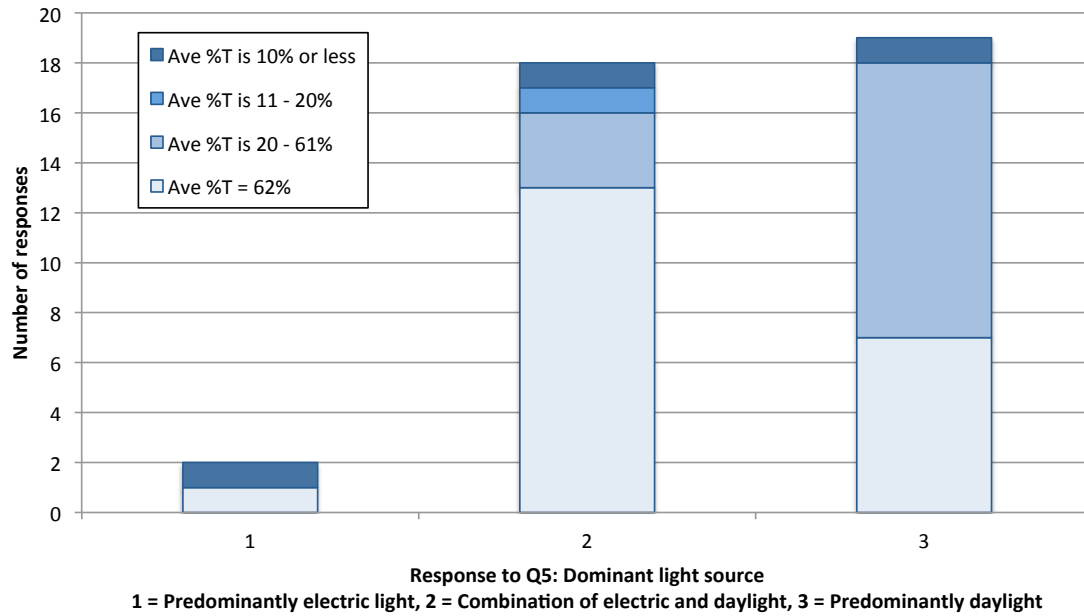
Figure 7.11, 7.12, 7.13 and 7.14 show the responses to each of the perceived lighting conditions questions (Q3-6) and the area-weighted average transmittance of the glazing at the time of response. In general, the graphs do not indicate a relationship between EC window transmittance and perceived lighting conditions, with a range of response categories represented under a diverse range of glazing transmittances.



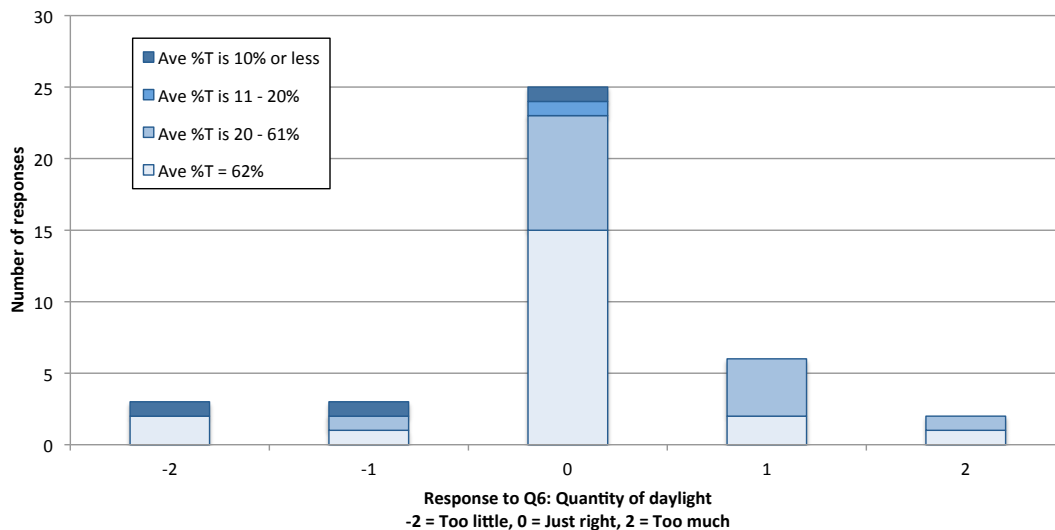
**Figure 7.11** Perceived light level and average EC glazing transmittance



**Figure 7.12** Perceived distribution of light and average EC glazing transmittance



**Figure 7.13** Perceived dominance of daylight and average EC glazing transmittance



**Figure 7.14** Perceived quantity of daylight and average EC glazing transmittance

Based on these results, no obvious relationship can be identified between EC window tint level and participants' perception of light level in the room. This may be due to a number of factors, as explained previously: namely the fact that the windows were tinted at less than half of the questionnaire response times and the frequent use of blinds in room B, potentially obscuring the window.

### 7.2.3 Experience of glare (Q 7 – 11)

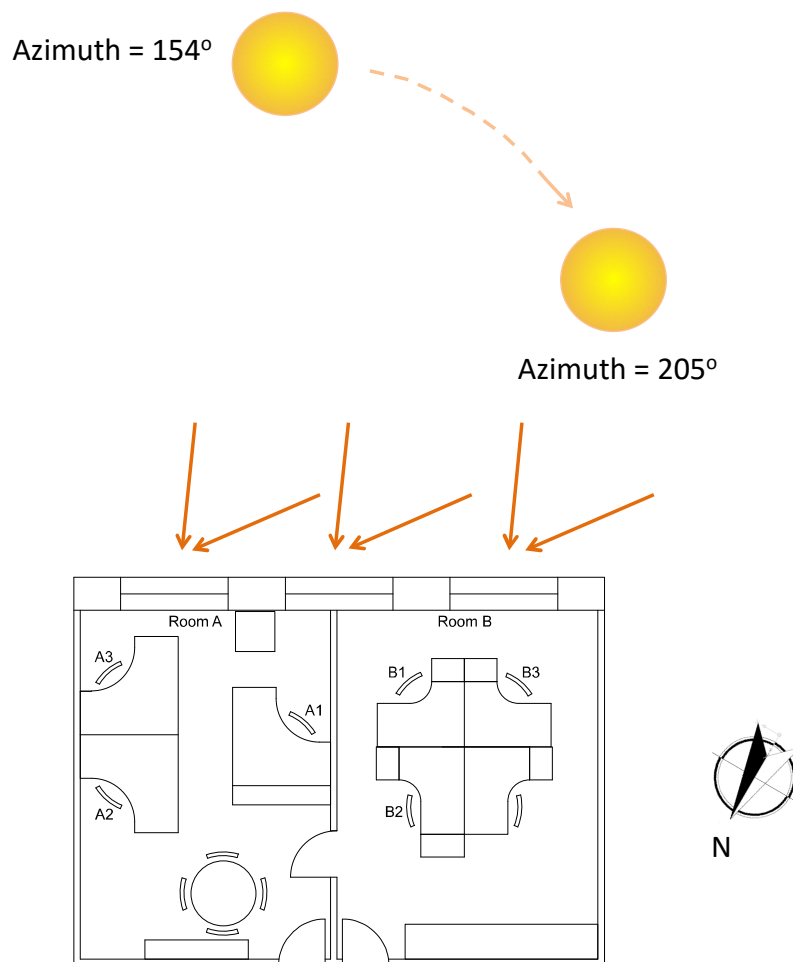
Questions 7 and 9 asked participants whether they were experiencing screen reflections or direct glare at the time of responding. Q8 was a follow-up question that was asked if a participant gave a “yes” response to Q7, asking them to identify the source of the screen reflections. Similarly, Q10 and Q11 were asked if a participant responded “yes” to Q9, asking them to identify the source and rate the severity of the glare.

There were very few “yes” responses to these questions, which could be interpreted as an indication that visual discomfort was a rare occurrence. However, these results are more likely a reflection of conditions at the times when participants completed questionnaires, *i.e.* not necessarily at times of clear skies and direct sun in the room, when discomfort would be more likely. There were five “yes” responses to Q7, indicating that the participant was experiencing screen reflections, and just two “yes” responses to Q9, indicating that the participant was experiencing direct glare at that time. In all cases, the windows were cited as the cause of the reflections or glare, and in the case of the two “yes” responses to Q9, the discomfort was rated as “intolerable”. Table 7.3 gives details of the “yes” responses, along with the EC window condition, sun position and façade illuminance at these times.

**Table 7.3** Conditions at times when participants reported screen reflections or glare (*i.e.* a “yes” response to Q7 or Q9). The EC window conditions were recorded within the same minute that the questionnaire was completed.

Q	Date & time	Part.	Average %T of EC window	Sun position		Façade illuminance (klux)
				Azimuth (deg)	Altitude (deg)	
Q7	15/05/2013 13:04	B3	34	185.2	56.3	10.5
	21/11/2013 12:29	B1	43	191.7	16.6	25.0
	11/12/2013 13:11	B3	24	198.8	12.3	12.3
	23/01/2014 12:25	B1	24	184.1	17.9	29.3
	26/02/2014 10:36	B3	8	154.0	25.5	80.7
Q9	21/11/2013 12:29	B1	43	191.7	16.6	25.0
	11/12/2013 13:42	B2	62	205.7	10.6	8.2

It can be seen that all the “yes” responses came from participants in room B, and that most occurred around lunchtime. Most of the responses occurred during November – February, at times of low solar altitude. In all but one case, the average transmittance of the glazing was below 62%, indicating that the windows were at least partly tinted. The February response is interesting because it suggests that participant B3 was experiencing screen reflections despite the fact that all the glazing was tinted to a low transmittance level ( $T = 8\%$ ). It can also be seen that all five responses occurred when the solar azimuth was between  $154^\circ$  and  $205^\circ$ , almost perpendicular to the façade to a southwest position, as shown in Figure 7.15. It can also be seen that the seating positions of participant B1 and B3 were such that they were more likely to experience screen reflections when there is direct sun on the façade.



**Figure 7.15** Solar azimuth when participants reported screen reflections or glare (*i.e.* a “yes” response to Q7 or Q9)

It can also be seen from Table 7.3 that, in most cases, sun altitude was low, which is to be expected, since low sun is more likely to cause visual discomfort. In one case, however, it was relatively high, at 56.3°. It is possible that in this case, reflections from external surfaces, or other unknown factors, were at play.

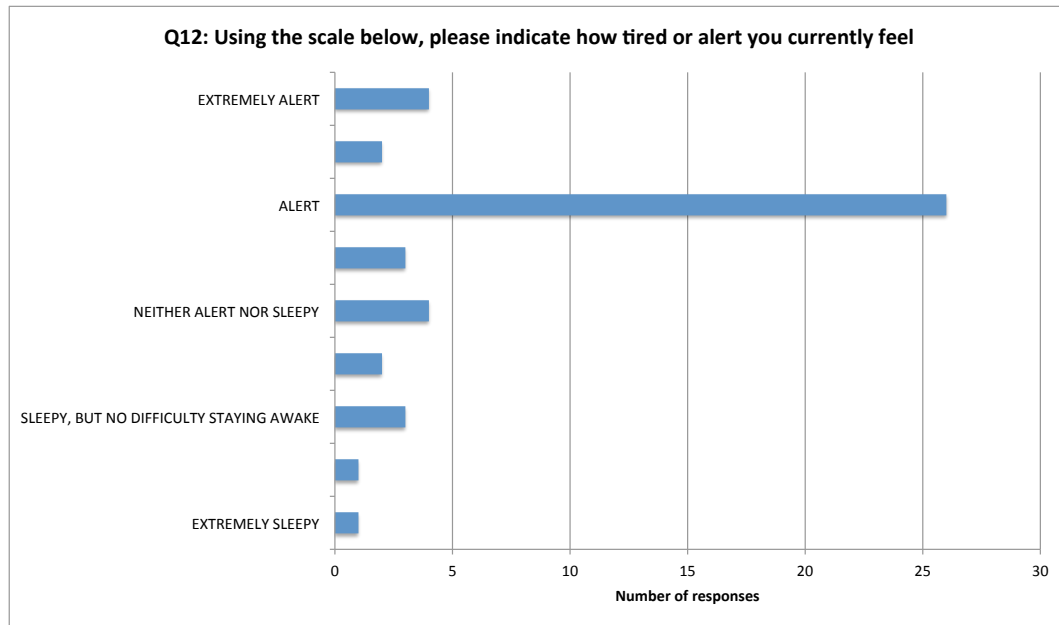
It is also notable that the façade illuminance is surprisingly low in all but one case. It is possible that the time stamp given by the questionnaire software was different to that used by the EC window control system clock. Thus, the apparently low façade illuminance at these times could be a result of “spiking” on the façade sensor, *i.e.* variable weather conditions that caused rapid changes in the façade illuminance reading; an issue which is explored in detail in Chapter 8.

#### **7.2.4 Other questions**

The results of the other questionnaire items are described below. The data from most of these questions (12, 13, 14, 15, 18 and 19) were analysed with the corresponding EC window state as part of the investigation into the effects of EC glazing tint colour on range of subjective parameters (see Chapter 9). Therefore, this section contains only the results and their interpretation, with the EC window condition at the times of response analysis covered later, in Chapter 9.

##### *Self-reported alertness (Q12)*

The self-reported alertness results are shown in Figure 7.16. It can be seen that, in the majority of cases, participants rated themselves as “alert”, with few responses at the extreme ends of the scale.

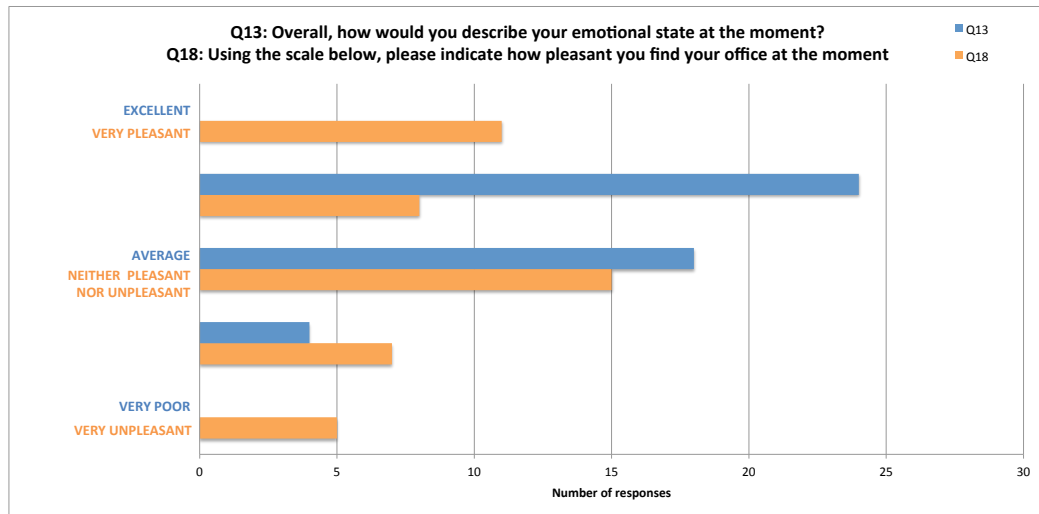


**Figure 7.16 Self-reported alertness (responses to Q12)**

*Self-reported emotional state and perceived pleasantness of office (Q13 & 18)*

Question 13 asked participants to rate their emotional state on a five-point scale ranging from “poor” to “excellent”, and question 18, how pleasant they found their office environment at that time, using a five-point scale ranging from “very unpleasant” to “very pleasant”. Due to the similarities in the scales used and to save space, the results of these two questions have been plotted together in Figure 7.17. It can be seen that the majority of responses to the emotional state question were in the category between “average” and “excellent”, and that there were no responses at all at the extreme ends of the scale. Most responses to the perceived pleasantness question were in the neutral (middle) category, but there were also a relatively large number of responses in the “very pleasant” category.

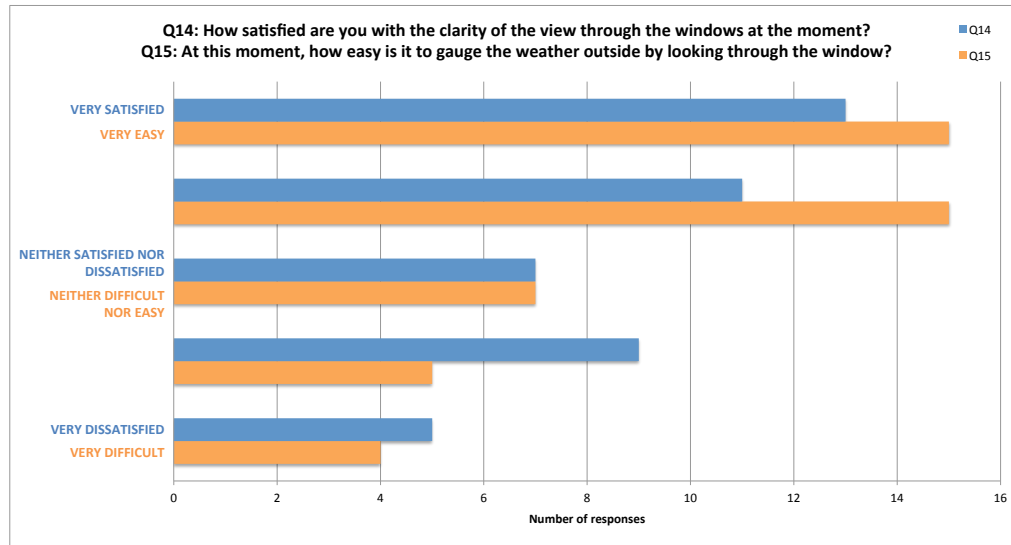




**Figure 7.17 Self-reported emotional state and perceived pleasantness of office (response to Q13 & 18)**

#### *View through the EC window (Q14 & 15)*

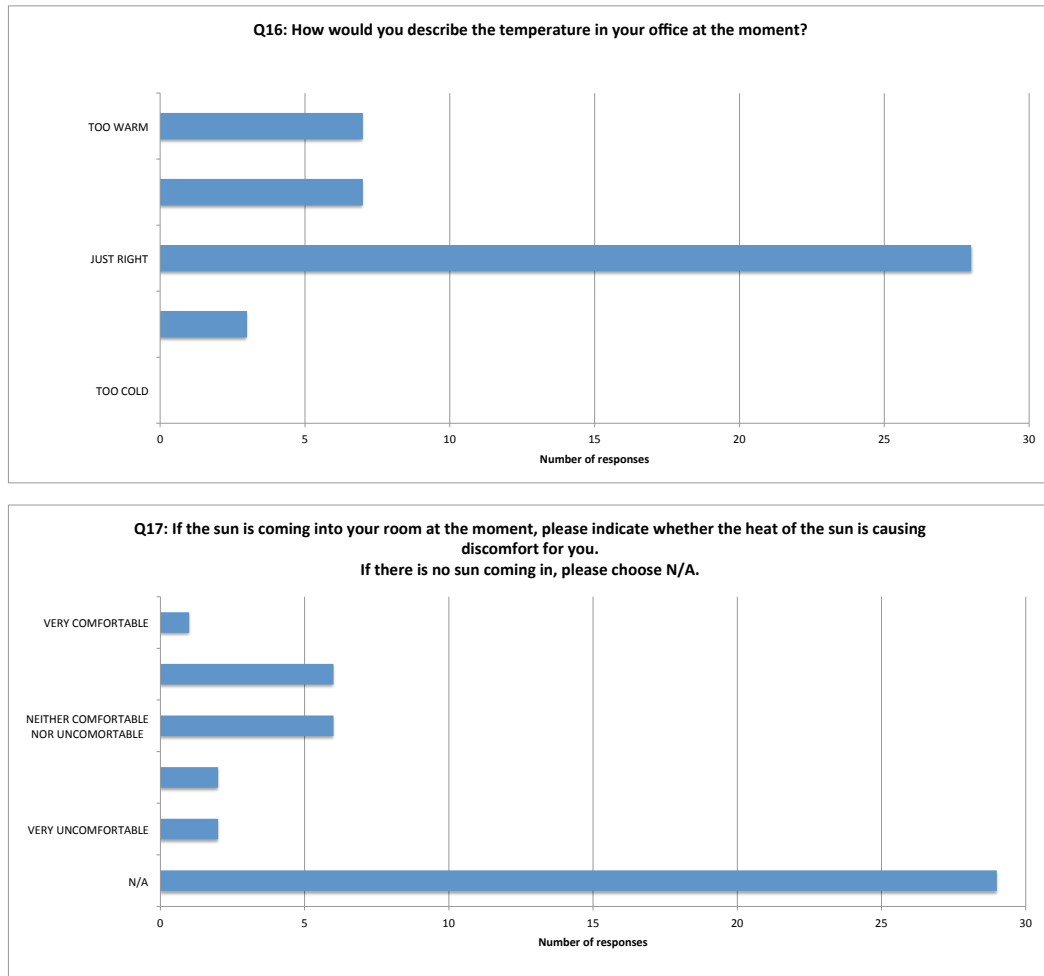
Questions 14 and 15 relate to the way in which the tinting of the glass affects the view out. In these questions, participants were asked about the clarity of the view out and the ease with which they could gauge local weather conditions by looking out of the window. Both questions used a five-point scale, and participants were asked to rate their satisfaction with the clarity of view from “very dissatisfied” to “very satisfied”, and the ease with which they could tell the weather conditions from “very difficult” to “very easy”. The results of both questions are plotted together in Figure 7.18. It can be seen that, in most cases, participants found it easy or very easy to tell the weather, and that they were mostly satisfied with the clarity of the view out. However, there were a considerable number of responses that indicated dissatisfaction with the clarity of the view out, and difficulty with being able to gauge weather conditions.



**Figure 7.18** Perceived clarity of view through the EC window and ability to judge weather by looking through it (response to Q14 & 15)

#### *Thermal conditions (Q16 & 17)*

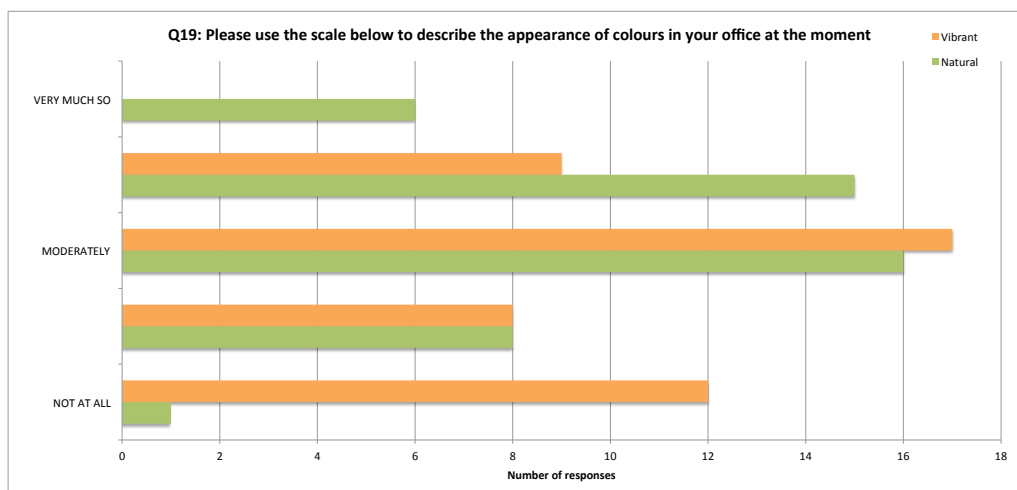
Questions 16 and 17 both concern solar overheating. In question 16, on a five-point bi-polar scale, participants were asked to rate the perceived thermal conditions in the room, from “too cold” to “too hot”. In question 17, participants were asked to indicate whether, if direct sun was present at that time, it was causing discomfort. If so, they were asked to rate this on a five-point scale ranging from “very uncomfortable” to “very comfortable”. As shown in Figure 7.19, most responses to question 16 were in the neutral “just right” category, and none were in the “too cold” category. In response to the question about unwanted heating from direct sun, in most cases participants chose “N/A”, indicating that there was no direct sun present at the time of response. This could be the case under cloudy conditions or when the sun’s position was such that it was not shining directly into the room, but could also be due to the tinting of the window or the presence of drawn blinds. For the small number of responses not in the “N/A” category, most were neutral or between neutral and “very comfortable”.



**Figure 7.19 Perceived thermal conditions in the room (response to Q16 & 17)**

### *Colour appearance (Q19)*

Question 19 was a two-part question in which participants were asked to indicate their perception of colours in the room, in terms of how natural and how vibrant they appeared. As shown in Figure 7.20, in most cases participants felt that colours were moderately natural in appearance, and there were a relatively large number of responses in the category between “moderately” and “very much so”. It can also be seen that most of the time participants found colours to be moderately vibrant, with no responses in the “very much so” category and a considerable number in the “not at all” category. As with other questions, the data from this item may not reflect the effect of the tinting on the perception of colours so much as the general perception of the colours in the room, since in many cases the glazing was not tinted at the time of response.

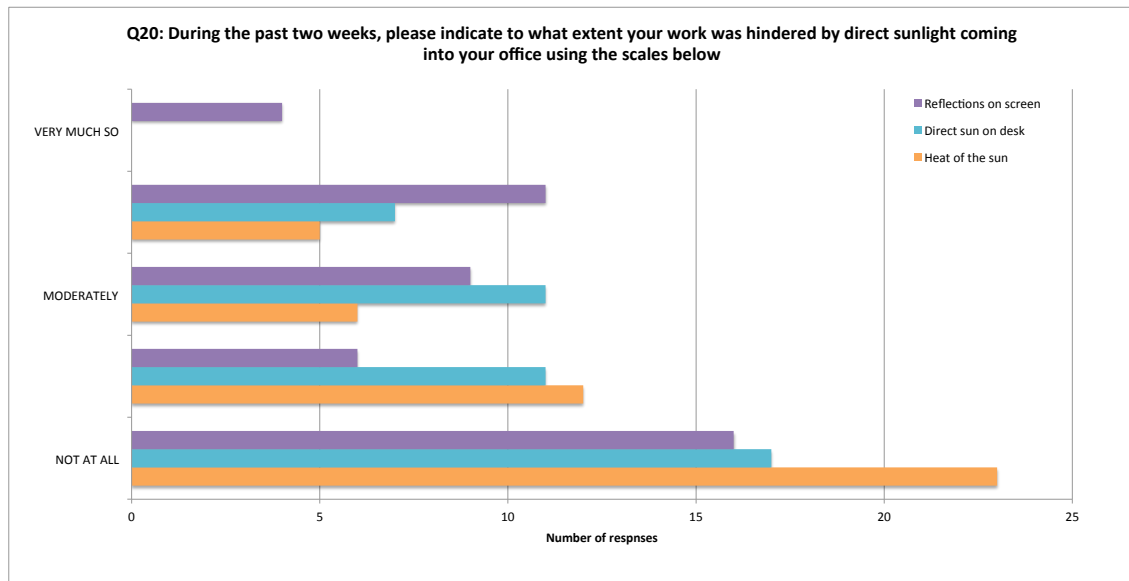


**Figure 7.20 Appearance of colours in the room (response to Q19)**

There were two parts to this question, relating to how “natural” and how “vibrant” participants felt that colours appeared. Both were on the same five-point scale, ranging from “not at all” to “very much so”.

#### *Negative impacts of direct sunlight over the preceding two weeks (Q20)*

This question differs from the others in that it was the only one that was not asked in the “present moment” context. Here, participants were asked to indicate the level and nature of disruption (to work tasks) caused by direct sun in the room during the preceding two weeks. The responses, shown in Figure 7.21, indicate that in most cases, participants had not experienced these problems much. However, the responses for screen reflections indicate that these were a more frequent problem for participants. For direct sun on the desk, the responses indicate that this was also felt to be a more-than-occasional problem. The heat of the sun appears to be the least problematic element of direct sun in the room.



**Figure 7.21 Negative impacts of direct sun in the room (response to Q20)**

There were three parts to this question, relating to (i) reflections on the screen, (ii) direct sun on the desk, and (iii) the heat of the sun. All three were on the same five-point response scale, ranging from “not at all” to “very much so”.

### 7.2.3 Measured internal lighting conditions at times of response

This section examines the internal luminous conditions, as described by HDR-derived metrics, around the times when participants responded to questionnaires. The analysis explores the relationship between perceived and measured lighting conditions in the space, addressing the question of whether the data collected in this study can be used to link measured lighting conditions and occupants’ perceptions of those conditions.

From the time stamp of each questionnaire response, the HDR images that were captured closest to the time of each questionnaire response were identified (*i.e.* within a maximum of 15 minutes). During the data collection period, a total of 47 questionnaire responses were collected, however there were only 35 for which corresponding HDR images were available from both cameras.

As explained in Chapter 5, eight luminance metrics were chosen for extraction from the HDR images. Only the first six metrics are used in this analysis, since they are taken to represent a reasonable range of aspects of the luminous

conditions in the room at the time when an image was captured. They are as follows:

- Min luminance (Min L)
- Maximum luminance (Max L)
- Mean luminance (Mean L)
- Median luminance (Median L)
- Standard deviation luminance (Std Dev L)
- Ratio of 75<sup>th</sup> to 25<sup>th</sup> percentile luminance (75:25)

There was one HDR camera located in room A for two-week periods only, and as the participant in room A did not provide many questionnaire responses, there was not enough data from room A to enable a meaningful analysis to be undertaken. Thus, this analysis relates only to participants in room B.

The positions of the two cameras in room B are shown in Figure 5.4. It can be seen that camera HDR1 is closest to the viewing position of participant B1 and B2, whilst camera HDR2 is closest to participant B3. With this in mind, the analysis is focussed on exploring possible relationships between the subjective perception of a given participant (questionnaire response) and the luminance metrics derived from the camera closest to the viewing position of that participant. Responses to questions about perceived lighting conditions (Q3 - 6) were plotted against the luminance metrics derived from the HDR image taken closest to the response time, and from the camera closest to the participant. The graphs are not shown here, but can be found in Appendix VII.

From the plots, some weak correlations were identified that occurred in the case of more than one participant, indicating that they may be noteworthy. Table 7.4 gives an overview of the relationships found. The small number of participants does not allow for rigorous significance testing, therefore the  $R^2$  values shown are only indicative of possible relationships.

**Table 7.4 Summary of relationships found in more than one participant**

Luminance metric	Subjective response	Relationship type	Participant	R <sup>2</sup> value
Min L	Perceived dominance of daylight (Q5)	Direct	B1	0.24
			B2	0.36
Mean L	Perceived dominance of daylight (Q5)	Direct	B1	0.22
			B2	0.28
			B3	0.30
Median L	Perceived dominance of daylight (Q5)	Direct	B1	0.33
			B2	0.13
Std. Dev.	Perceived dominance of daylight (Q5)	Direct	B1	0.18
			B2	0.14
			B3	0.36
75:25	Perceived dominance of daylight (Q5)	Direct	B2	0.14
			B3	0.54
Mean L	Perceived daylight level (Q6)	Direct	B1	0.16
			B3	0.30
Std. Dev.	Perceived daylight level (Q6)	Direct	B1	0.13
			B3	0.24

Whilst the results do suggest that there may be a relationship between some luminance metrics and perceptions of some aspects of lighting conditions in the space, the small number of participants in this study means that these results should be tentatively asserted. The following relationships were present in all three participants, indicating that they may be important:

- Perceived dominance of daylight in the room increases with increasing mean luminance.
- Perceived dominance of daylight in the room increases with increasing standard deviation of luminance.

Five of the eight relationships described in Table 7.4 involve the subjective variable “perceived dominance of daylight” (Q5). This question has only three response categories, and it is possible that the small number of responses, combined with the limited diversity of responses, mean that relationships are more likely to be apparent, whether or not they exist in reality. However, the relationships are logical and in line with expectations of the relationship between these variables.

The small sample size in this study means that further quantitative analysis is not possible. In order to fully validate these findings, this process should be repeated with a larger number of participants providing more subjective response data. It would be beneficial if HDR images were captured at exactly the same time as participants' responses, since daylighting conditions might change in the interval between participant response and HDR capture (a maximum of 15 minutes), especially on days with variable weather. Furthermore, the location of the cameras should be carefully considered. In this case, they were not located at the eye position of participants, and it is possible that greater levels of correlation might be found between variables if cameras were located closer to participants' viewing positions.

#### **7.2.6 Summary**

The questionnaire data provided useful "snap shots" of participants' perceptions at the times when they responded. There is a limit to how much these data could be used to identify links between occupants' responses and EC window tint state, due to the small quantity of questionnaire data at times when windows were tinted and the fact that blinds were frequently used in room B. Nonetheless, the results indicated that participants were largely satisfied with various aspects of their environment at the times when they responded to questionnaires.

A range of luminance metrics was extracted from HDR images captured around the times of questionnaire responses (in room B) so that the relationship between the perception of lighting conditions and the measured luminance conditions in the room could be explored. The results indicated possible relationships between a number of perceived and measured lighting variables. However, due to the small number of participants involved in this study, further work would be required to validate the results.



### 7.3 Interview results

As explained in Chapter, the interviews were intended to deliver in-depth information about participants' experiences of EC glazing over the course of the data collection. A total of six rounds of interviews were conducted over a period of 16 months. Apart from the final set of interviews (in April 2014), interviews were held with the four main study participants; one from room A, and the others from room B. For the final set of interviews, two other occupants from room A were approached and agreed to be included, thus providing a more balanced data set across the two rooms.

Table 7.5 summarises the data collected from the interviews. The first interviews after the window installation were held in November 2012, and conducted thereafter approximately every 3-4 months until the final set of interviews in April 2014. Participant A1 was not available for the January 2014 interview. The interviews were audio recorded and transcribed verbatim. However, a technical problem led to the loss of the original audio recordings of the July 2013 interviews; as a result, only an edited version of these transcripts was available for analysis.

**Table 7.5 Interview data set summary. OT = Original transcript, ET = Edited transcript (original not available)**

Participant	Date of interview					
	Nov 2012	Mar 2013	Jul 2013	Oct 2013	Jan 2014	Apr 2014
A1	OT	OT	ET	OT	None	OT
A2	None	None	None	None	None	OT
A3	None	None	None	None	None	OT
B1	OT	OT	ET	OT	OT	OT
B2	OT	OT	ET	OT	OT	OT
B3	OT	OT	ET	OT	OT	OT

The data underwent a two-stage analysis process. First, a thematic analysis was conducted, which identified a number of themes. Then, a content analysis was carried out that looked at the relative quantity of data within each theme, and how this varied over the course of the data collection.

### 7.3.1 Thematic analysis

The interview data were analysed using the thematic analysis technique, following the steps suggested by Braun & Clarke [2006]. This method was chosen because it allows the themes within the narrative data to be drawn out without the need for a pre-existing theoretical framework; it is thus well aligned with the exploratory nature of this study. Thematic analysis is also particularly suitable as it enables a more interpretative approach to be used, *i.e.* considering the meaning behind the use of certain words or phrases, rather than the occurrence of certain words or phrases *per se*. It is a flexible method that has the ability to distil the essence of the data whilst enabling its richness to be preserved.

The transcripts were thoroughly reviewed, and each segment (*i.e.* sentence, comment or phrase) of the participants' responses was coded. For example, negative comments about the length of time it takes the EC windows to respond to changing conditions might be given one code, whilst positive comments about the responsiveness of the EC windows would be assigned a different code. In this sense, the segments were not coded just according to subject matter (*e.g.* transition time/window responsiveness), but also the perspective of the interviewee (*e.g.* how they felt about the transition time of the window). A segment could be assigned more than one code, *i.e.* if it expressed a view on more than one aspect, or conflicting views on the same aspect. This process resulted in a total of 59 different codes, though some were deleted during subsequent revisions. The codes were grouped into themes, which are listed in Table 7.6.

**Table 7.6**      **Interview data themes**

	<b>Theme</b>
(i)	General attitude towards EC windows
(ii)	Glare control effectiveness
(iii)	EC window controls & settings
(iv)	The effect of tinting on the room & view out
(v)	Lighting system
(vi)	Study participation
(vii)	Thermal conditions

The resultant themes were further classified in terms of polarity, *i.e.* as positive, negative and neutral perspectives. Figure 7.22 provides an illustration of the themes in the form of a mind map; this is considered to be a thematic map of the interview data.

In the sections that follow, each theme will be discussed in turn, with examples of comments made by participants used to illustrate the points.

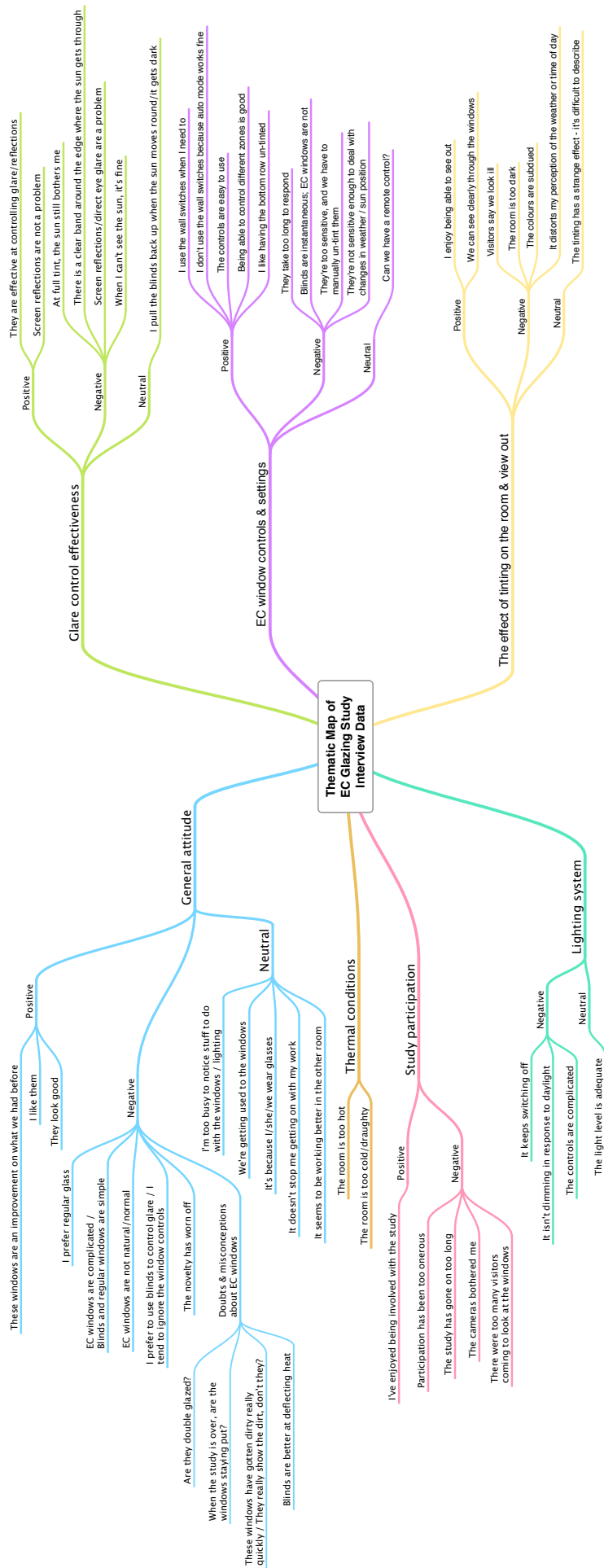


Figure 7.22 Thematic map of the interview data

*(i) General attitude towards the EC windows*

This theme contained general comments about the windows that were not easily attributable to one particular aspect or function. They are considered to embody the “general attitude” towards the technology, to take account of the fact that a participant might express a polarised view of the windows without being able to articulate further why they feel as they do, or indeed to rationalise their viewpoint.

Among the positive comments were those such as: “They’re lovely, I really do like them. I like the cleanness and the crispness of them, they’re very high-tech, modern.” (Participant A1, January 2014), and “I think on the whole I’m really pleased that we’ve been lucky enough to have them. And the comments from visitors have been really positive. I feel quite lucky.” (Participant A2, April 2014).

Negative perspectives were more numerous, and were one of three main types:

- Those that simply expressed a preference for traditional windows over EC windows.
- Those in which the preference for traditional windows was explained further.
- Those that expressed a deeper level of mistrust or unease about the EC windows.

In the first type were comments such as: “I’d rather have clear windows with blinds. I don’t think they’re working properly, not for me anyway.” (Participant B2, March 2013). This also includes comments in which participants expressed a negative view on behalf of others, *e.g.* “I’m still finding it difficult, as the other girls are.” (Participant B2, November 2012). In the second type, some attempt was made to justify the negative view of EC windows, such as that they are too complicated or that they are unnatural compared with traditional windows and blinds, *e.g.* “You’re just used to having clear windows, aren’t you, and not them fluctuating and changing depending on the light.” (Participant B1, March 2013), and: “They’re not as natural looking as this (gestures to interview room window, which is not EC).” (Participant B2, April 2014). The third type of comment forms a sub-group that indicated a deeper lack of trust in the technology. (They are

given the heading “Doubts and misconceptions about EC windows” in the thematic map shown in Figure 7.22.) These comments are somewhat abstract compared with the more straightforward expressions described above. They include such comments as “Are they double glazed?” (Participant B1, November 2012), “I’m assuming that once the project’s over, that the windows stay?” (Participant B3, October 2013), and “It accumulated so quickly though, this dirt on the inside, didn’t it? (Participant B2, April 2014). In the March 2013 interview, participant B3 commented that: “A blind would probably have more impact on deflecting heat, because the windows aren’t going to deflect that are they?”; a misconception that nonetheless suggests a level of scepticism about the performance of EC windows. These latter types of comment all indicate a certain level of doubt and unease about the technology.

Comments that were not explicitly positive or negative were classed as neutral. These included comments such as: “I haven’t really noticed. I haven’t paid that much attention to it. Our office is so busy, it’s hard for you to take the time out.” (Participant A1, November 2012), and “I suppose we’ve got used to it.” (Participant B1, April 2014).

#### *(ii) Glare control effectiveness*

This theme encompasses comments about the perceived ability of the EC windows to control glare. On the positive side were comments such as: “A bit like a good pair of sunglasses (laughs). Exactly like that. They don’t discolour, they just take away the glare.” (Participant A3, April 2014). As with other themes, the negative comments were more numerous. They included comments that suggest that even when the windows were fully tinted, the sun still caused glare or reflections, *e.g.* “I can see the sun through it even at the darkest tint.” (Participant B2, March 2013). There were some comments made about the non-tinting boundary area, a narrow band of glass close to the window frame on which no EC coating was applied, suggesting that this reduced the windows’ effectiveness to fully control glare. There were also comments suggesting that, as long as it was not sunny, there were no problems, the corollary of which is that when the

sun was out, there was more likely to be a problem. For example: “I’m fine on days like this, when there’s no sun.” (Participant B2, April 2014).

### *(iii) EC window controls & settings*

Within this theme are comments about interaction with the controls and perceived control system performance (*i.e.* responsiveness). The positive comments were strikingly diverse, expressing converse attitudes towards using the controls, both passive and active. For example, participant A1 said in the October 2013 interview: “I don’t use them at all. I don’t need to. What I find strange is that, prior to the new windows, I was always having to adjust the blinds, but since we’ve had the new windows, I don’t have to use the switch. So the windows, they do work.” This statement indicates that whilst she tended not to use the manual controls, it was because she was satisfied with the control provided by the EC windows in automatic mode. In contrast, participant A3 said in April 2014: “The bottom windows, you can darken them manually and it reacts very quickly, which is excellent.” This implies that she was happy to use the controls because she trusted the EC windows to respond to her needs.

Other positive views within this theme indicated that participants were happy with the way the windows were zoned and the fact that each zone could be controlled individually and allocated different thresholds. For example, participant A2 said (in April 2014) “Yes, definitely (likes having the bottom row un-tinted). Especially at that height, when you’re sitting down, because it’s at my eye level.”

The negative comments expressed a reluctance to engage with the technology by using the manual controls, with the overriding sentiment being that even if manual controls were used, it was unlikely to deal effectively with glare. This despondency was expressed in a number of comments, such as: “They don’t darken very quickly, which is one of the reasons we’ve been using the blinds.” (Participant B3, October 2013) and “When you press the button it does take a while to change. And even when the sun comes out and it responds automatically, it still doesn’t change quickly. So if anything can be done about

that..." (Participant B1, November 2012). There were also comments indicating that, in automatic mode, the windows were either too sensitive or not sensitive enough, *e.g.* "But even then, yesterday it was a bit temperamental, and kept plunging us into blue, even though it was quite cloudy outside." (Participant B3, March 2013) and "I think on automatic, it's gone the other way, it's gone to the other extreme and it's not responsive enough." (Participant B3, April 2014). Whilst these perceptions could be perceived as conflicting, they could in fact be two facets of the same aspect, since window performance could be perceived to be somewhat erratic on a changeable day, when façade illuminance fluctuates rapidly. Under these conditions, the windows could be perceived as tinting when not required and not tinting when required. This issue will be discussed in more detail in Chapter 8 in the context of control system behaviour.

Participant B2 (March 2013 and January 2014) and B1 (November 2012) made semi-joking comments indicating that they would like to be able to control the windows using a remote control, *e.g.* "A remote would be good (laughs). Because then you're in control, and you don't have to stop what you're doing." (Participant B2, January 2014). These comments were classed as neutral, and although mentioned to the manufacturer, were not considered for addition to the system, partly because it was not available at that time. (However, remote control is now possible using an interface on a tablet or mobile phone). It is notable that participant A3, who was a proactive user of the window controls, sat close to the windows. The comments about a remote control came from participants B1 and B2, whose seating positions were such that they would have to leave their seat to use the manual controls. Hence, although the remote control comments were made somewhat lightly, they could be indicative of a relationship between reluctance to use the window controls and distance from them.

#### *(iv) The effect of tinting on the room & view out*

This theme contains perspectives about how both the interior and the view through the window appears when the windows are tinted. Positive comments were about the view out, and the majority of these were made during the first



interviews following the window retrofit. Participants indicated that they were enjoying being able to see out, and that it was an improvement upon their previous windows, which had suffered from inter-pane fogging that obscured the view. Some comments related to the benefit of having a clear view even when the windows were tinted, *e.g.* “And it’s clear when it’s lighter and when it’s darker. I said to one of the others the other day, is that a crow on that roof over there?” (Participant B2, November 2012). Negative comments within this theme related to both the room appearance and view out. Several comments indicated participants’ perception that tinting had an adverse affect on the appearance of occupants’ skin tone, such as: “I mean, comments have been made, like “you all look grey”, like we’re ill! I think it’s the shadow from the tinted windows making us all look different colours.” (Participant B1, November 2012). Other comments related to the perception that tinting made colours in the room appear dull, and the room appear darker, *e.g.* “It just looks a bit twilight-y, dusky. Greyish.” (Participant B2, October 2013). There was a perception among participants from both rooms that the tinting distorted the view of the sky, making it more difficult to discern weather and time of day. This view was reflected in comments such as: “I think if you’re looking out to see what’s it’s doing in terms of weather, yes I think it does matter. I think they need to be not tinted to see that. It depends what you’re looking out for. If you’re looking out to determine if you need to take a brolly with you or not, or if the could looks like it’s going to rain, if there’s a slight tint on them, it sometimes looks like it’s going to rain when it actually isn’t. So it can kind of give you a wrong perception of the weather, I think.” (Participant B3, July 2013). A few comments expressed a view that the effect of tinting on the room appearance was difficult to describe. As this is neither positive nor negative, these types of comments were classed as neutral.

#### *(v) Lighting system*

Views about the lighting system were either negative or neutral. Negative comments reflected problems with the operation of the lighting, which were described in Chapter 6. They included negative views about the control interface (*i.e.* that it was too complicated), observations that the daylight linking did not

appear to be working, and complaints about the lights sometimes switching off for no apparent reason. Whilst the daylight linking function was mostly working in April 2013, the issue of lights switching off when the room was occupied and under non-bright conditions persisted, as reflected by comments such as: “I mean, last week, both (B2) and I kept getting up and switching it off and on again, because it kept dimming down.” (Participant B3, October 2013). A small number of comments indicated that light levels were adequate, and these were classed as neutral since they did not express an explicitly positive experience.

#### *(vi) Study participation*

Participants were asked about any issues with the data collection during each interview, and in the last set of interviews, in April 2014, questions on this aspect were widened to include views about participating in the study as a whole.

Perspectives about participation in the study contained both positive and negative elements. On the positive side, participants indicated that they had enjoyed being part of the study, and that it had been novel and interesting, *e.g.* “It’s been interesting, different. We’ve never had anything like that before. It’s amazing to see how the windows react to the light.” (Participant B1, April 2014).

Negative views about study participation differed between the two rooms. Participants B2 and B3 expressed a view that the self-report data collection was too onerous and that the duration of data collection was too long. For example:

- “Because we’ve had to do the monthly surveys and the smiley sheets, and also the interviews, it has been quite demanding.” (Participant B3, April 2014)
- “The questionnaires have been a bit irksome on occasion.” (Participant B2, April 2014).
- “It’s felt a bit too long. I’ve felt like a guinea pig for too long (laughs). It’s nearly two years.” (Participant B3, April 2014).

Participants in room A did not express a negative view about the duration or the nature of the self-report data collection. Participant A1 felt the presence of the

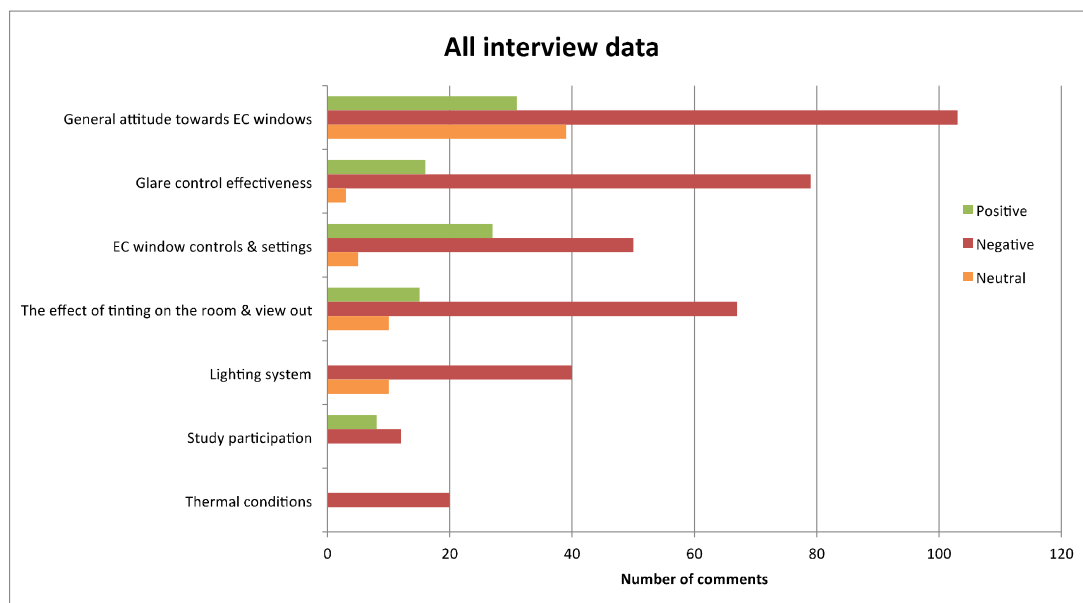
HDR camera and the increased number of visitors to the room during the initial few months after installation to be an issue. In the November 2012 interview, Participant A1 said: “The only thing is... there have been a lot of positives, because it’s nice and shiny and new and everything, but the only negative is the amount of distraction with people coming to see the windows. Like you’re in a tourist thingy. But that’s the only negative about having the windows.” In July 2013, she said: “I’m used to (the camera) being there, but it’s like an intrusion. It would be good to get that camera off my desk.” The camera in room A was subsequently removed and reinstated for two-week periods around equinoxes and solstices to reduce the inconvenience to occupants in that room, as explained in Chapter 5.

*(vii) Thermal conditions*

This theme includes comments about perceived thermal conditions in the rooms. There were no positive or neutral comments within this theme, only negative, and these reflected a perception that the room was either too hot or too cold. Due to differences between individuals’ preferred temperature, some occupants were more liable to feel that the room was too cold or draughty, whilst others tended to find their room too hot. However, participants’ comments did not generally indicate that they associated their thermal discomfort with the EC windows. One participant felt that there was a general issue with temperature control in the building: “It (the building) has these weird sort of temperature glitches. So, yesterday it was baking, but then a few weeks ago it was cold. There’s no happy temperature in our building, and I’m not sure if the windows have got any part to play in that anyway.” (Participant B3, October 2013).

### 7.3.2 Content analysis

A content analysis was carried out on the interview data to supplement the results of the thematic analysis. The purpose was to gain insight into the relative importance of each theme, by quantifying the data contained within them. This method was chosen because it can add a quantitative dimension to the results, and is appropriate as a supplementary analysis method within the context of a mixed methods study [Robson, 2002, page 352]. The unit used for the content analysis was a coded comment, which could be made up of one sentence or a small number of short sentences expressing the same point. Comments, rather than words, were chosen to avoid over-representing negative comments, since typically, more words are used to express negative views than positive ones due to the negativity bias [Ito *et al.*, 1998]. It is acknowledged that this measure might still overestimate the significance of the negative views since negative feedback is more likely to be reported than positive feedback, however, this approach does give some useful indications about the relative strength of each theme within the interview data. Figure 7.23 shows the results of the content analysis for the body of interview data.



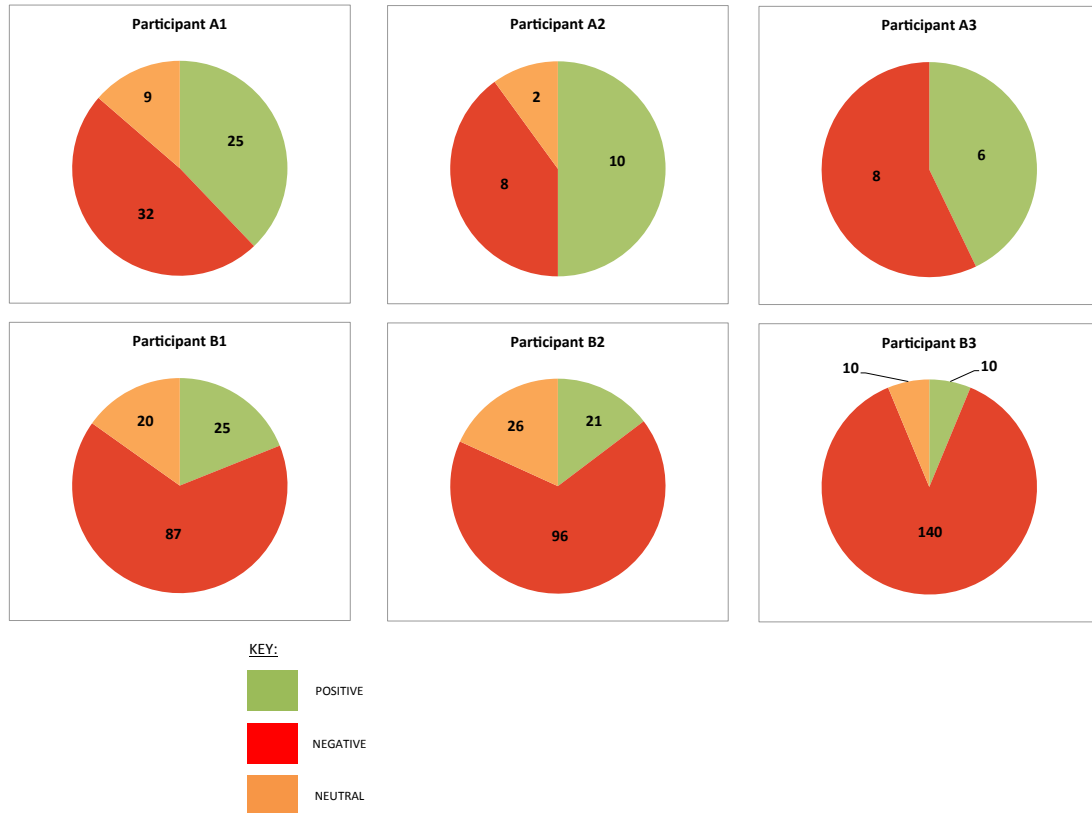
**Figure 7.23** Interview data by number of comments in each theme

It can be seen that a negative general attitude towards the EC windows is a dominant theme, and that negatively polarised themes are generally dominant. However, when taken as a whole, the interview data does not describe the experience of individual participants, and in particular is under-representative of participants in room A, since the bulk of the interview data came from room B participants. Thus, a further sub-group content analysis was undertaken to investigate the relative importance of themes within specific cohorts of interview data. The data set was broken down as follows:

- Per-participant and per-room
- Per-participant over time
- Final interviews only (all participants)

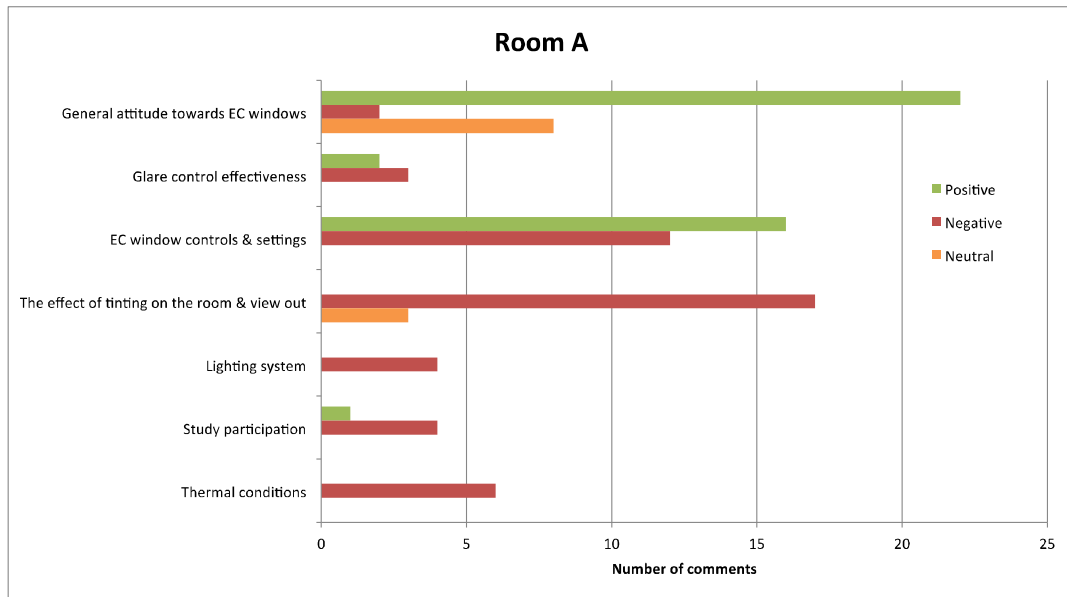
#### *Per-participant and per-room*

Looking at each participant individually on the basis of positive, negative and neutral themes shows that the negative themes are generally more dominant for the room B participants compared with the room A participants, as shown in Figure 7.24.

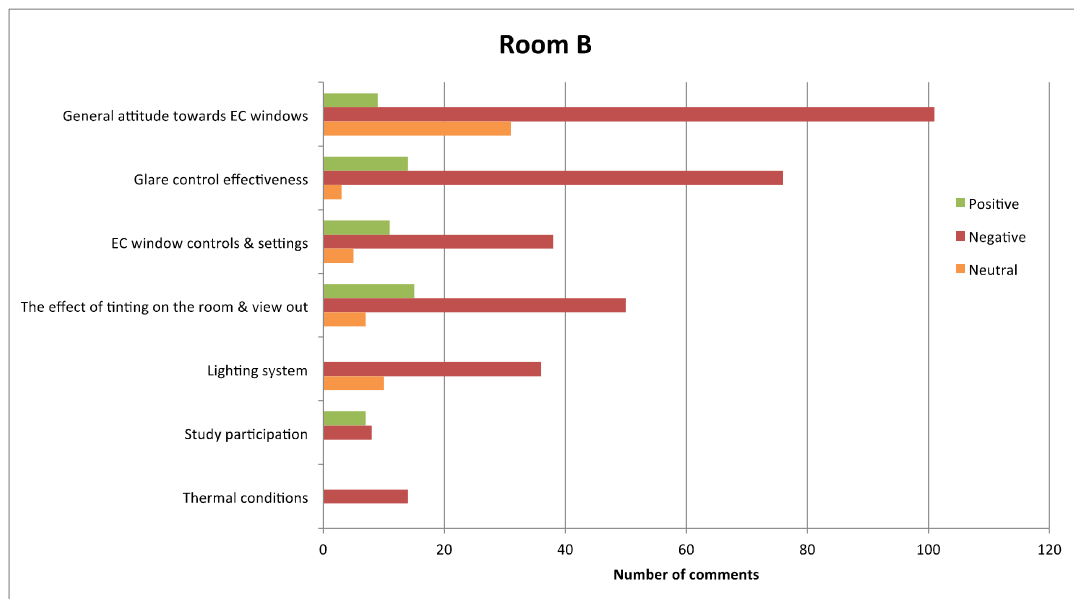


**Figure 7.24 Interview data by number of comments in the positive, negative and neutral themes for each of the six participants, with the number of comments indicated**

This trend is further illustrated in Figure 7.25 and 7.26, in which the number of comments within each theme is shown for each room. It can be seen that in room A, the positive themes are more prevalent, with positive general attitude towards the EC windows being most dominant. The results for room B are very similar to those for all interview data, which stands to reason since most of the body of interview data comes from room B participants.



**Figure 7.25 Room A interview data by number of comments in each theme**



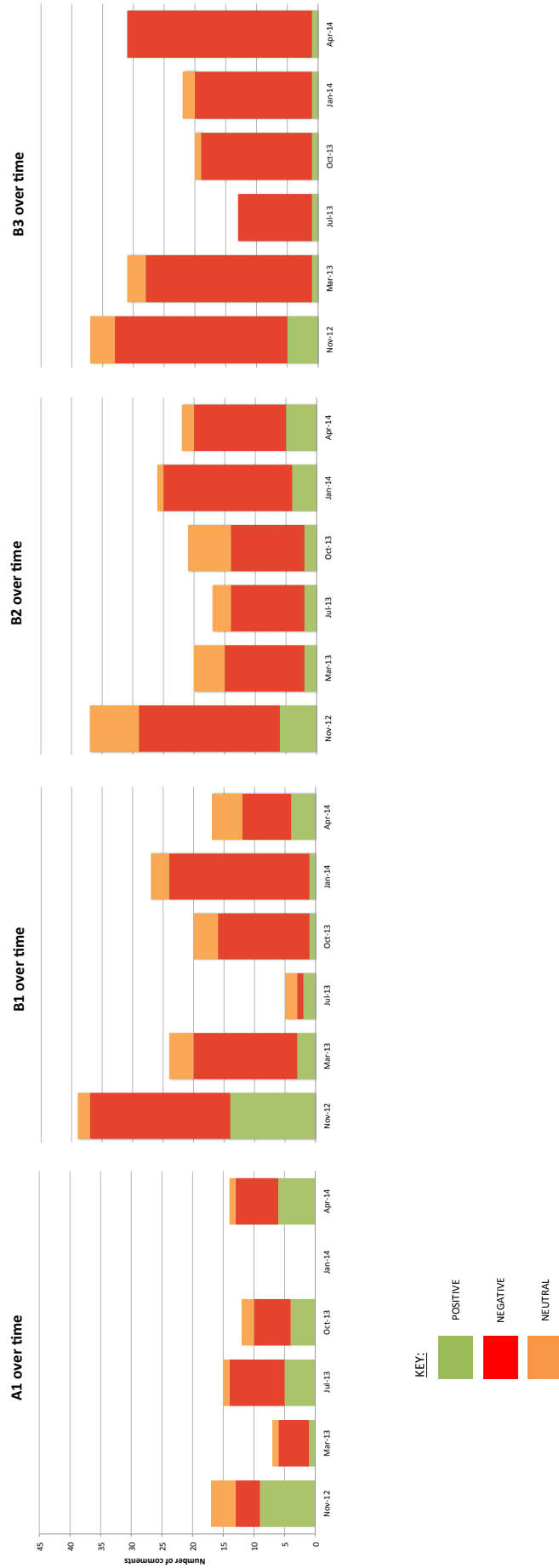
**Figure 7.26 Room B interview data by number of comments in each theme**

### *Per-participant over time*

It is also useful to look at how the differently polarised themes (*i.e.* positive, negative and neutral) varied over time. This is only possible for the main four participants, since they were interviewed multiple times during the course of data collection.

The results are shown in Figure 7.27. It can be seen that, across all participants, the positively polarised themes are more dominant in the first interview compared with subsequent interviews. It is also notable that there is generally more data (*i.e.* a larger number of comments) in the first interviews compared with the other interviews. This may reflect a perception of the EC windows as being a novelty at the time of the first interviews, and that general enthusiasm about the windows and the study may have been more prevalent earlier in the data collection. In the July 2013 interviews there is a noticeable dip in the volume of data and, for some participants, a reduction in the quantity of negative content. It is probable that the higher solar altitude at this time of year meant that participants had fewer visual discomfort issues to discuss. In addition, a smaller amount of data was available for these interviews because of the loss of the original transcripts. For participant A1, the positive themes continue to make up a considerable proportion of the total and the proportion of negative themes remained more or less consistent over the data collection period. In contrast, the room B participants' interview data show a reduced number of positive-theme comments compared with the first interview.

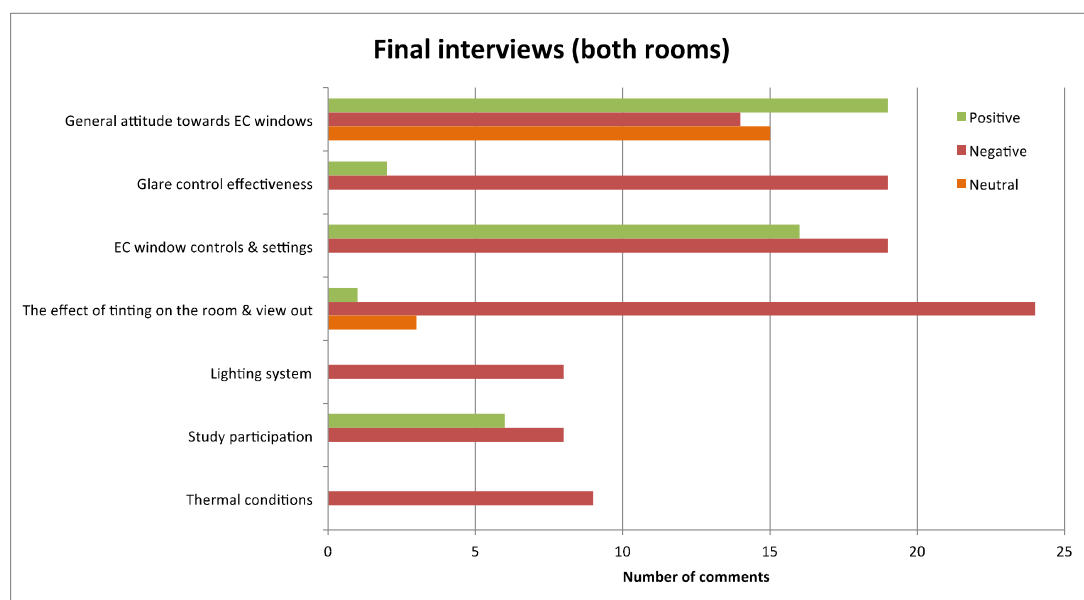




**Figure 7.27** The variance of theme polarity over time by number of comments for each of the main four participants

### *Final interviews only (all participants)*

The results for the final interviews give arguably the most balanced view, since this data set contains a more equal split between room A and room B. In these results, shown in Figure 7.28, it can be seen that whilst a positive general attitude towards the EC windows is relatively dominant, the most dominant theme is the negative perception of the effect of tinting on the room and view out. Negative views of the glare control effectiveness of the windows, and both positive and negative views of the window controls and settings are also relatively dominant.



**Figure 7.28** Final interview data by number of comments in each theme

## 7.4 Discussion

The daily experience sheet data shows that participants' satisfaction with the EC windows was generally higher during the summer period than other times of the year. This suggests that their experience was linked to seasonal variation, and specifically solar altitude. In the summer months, when solar altitude was higher and the sun did not penetrate very deeply into the room, participants reported a higher degree of satisfaction than in the winter months, when solar penetration was more frequent. The exception to this is participant A1, who consistently indicated that she was completely satisfied with the windows. Pronounced dips in satisfaction also occurred in January 2013 and October 2013. In each case, using the qualitative data provided by participants via additional comments, these dips were linked to problems with glare mode operation and problems with the lighting system, respectively.

The questionnaire data provided useful insights into the experience of participants at the times when they responded. A lack of data from participant A1 made it difficult to draw comparisons between the experiences of occupants in the two rooms. Nonetheless, the results indicated that participants were largely satisfied with various aspects of their environment at the times when they completed questionnaires. Responses to questions about glare and reflections indicated that participants were rarely experiencing visual discomfort at the times when they responded, but when they did report glare or reflections, the source was always identified as the windows. A study of conditions at the times when participants did report glare or reflections indicated that, in all but one case, sun altitude was relatively low and that not all of the glazing was tinted, *i.e.* more shading could have been provided by using the manual EC window controls to tint the windows further.

The responses to questions related to perceived lighting conditions in the room and the EC window state at the times of response were examined to explore the relationship between them. No obvious relationships were found, probably due to (a) the frequent use of blinds in room B, from where most questionnaire responses originated, and (b) the fact that the glazing was not tinted at more than half of the questionnaire response times.

A range of luminance metrics was extracted from HDR images taken at or near the time of a questionnaire response in room B. This enabled the exploration of possible relationships between the perception of lighting conditions in the room and measured luminance conditions in the room at the time of response. The results indicated possible relationships between various perceived and measured lighting variables. The relationships with the strongest indications (based on being present for all three participants) suggest that perceived dominance of daylight in the room increases with (a) increasing mean luminance and (b) standard deviation of luminance. This indicates that, as well as mean luminance, the spatial variation of luminance in the room (as indicated by standard deviation) might be an important factor in the perceived daylight level in the space. However, further work would be required to validate these results due to the limited quantity of data involved in this analysis.

The thematic analysis of the interview data highlighted several issues that were important to participants. A content analysis based on the number of comments within each theme indicated the relative importance of the various themes, for the interview data as a whole and for individual participants. A negative view of the effect of glazing tint on the room and view out was a consistently important theme for participants in both rooms. Within this theme, participants expressed a concern about the effect of window tinting on the ability to judge local weather conditions, and indicated that it could distort their perception of the time of day. Some also suggested that when the glazing was tinted, it made skin tones look grey and colours in the room appear duller.

In room A, participants had many positive things to say about the windows, including that they were modern, effective and that the controls were easy to use. In room B, participants had many negative views about the EC windows, and these were often expressed as an unfavourable comparison with traditional windows and blinds. The main issues were (a) that the windows did not tint quickly enough and (b) that the sun was too bright to be viewed comfortably through the window even when the glazing was fully tinted. These concerns were reflected in room B participants' views about the EC window manual controls. They reported that they usually went straight to the blinds to address

glare or reflections without trying to tint the window manually first, because they did not believe that the EC window alone would be sufficient. Many indicated that they preferred traditional windows and blinds because it was an instantaneous solution to glare control, despite the fact that blinds would completely obscure the view through the window. This suggests that the view out may be less important to users than the need to deal quickly with visual discomfort.

There were many positive views expressed about the fact that the windows were zoned, namely that each zone could be individually controlled and that the upper and lower zones had different thresholds, meaning that the lower zones were tinted less often than the upper ones. Participants indicated that they felt that this was a useful feature as it allowed them an un-filtered view out more of the time and diluted the effect of the tinting on the appearance of colours in the room.

Thus, the interview data showed a marked contrast in experience between room A and room B. The experience of room A occupants appeared to be generally positive, whereas the experience of room B occupants seemed to be predominantly negative. This echoes the pattern that was evident in the initial reactions of occupants in the two rooms during the first few months after the windows were installed, as described in Chapter 6. It is possible that the views established during the critical early period became entrenched, which could explain the predominantly negative views of the EC windows held by participants in room B. Other factors may also have contributed to this, including differences in desk layout between the two rooms, social effects and the impact of study participation. These issues are explored in Chapter 10.

## 7.5 Summary

The results of the self reported data collection and analysis have given a detailed insight into occupants' perspectives on EC windows over a longitudinal period.

An analysis of the questionnaire data relating to perceived lighting conditions in the room and the EC window state at the times of response did not reveal any relationships. An analysis of the same questionnaire data with corresponding internal conditions, as measured by HDR-derived luminance metrics, did suggest possible relationships between some perceived and measured lighting variables, but with the limited number of data points involved, they are noted with caution.

The interview data provided a rich account of users' experiences of EC glazing. The data strongly indicates a contrast in experience between occupants of the two rooms. Participants that worked in room A were generally positive about the EC windows, whilst those in room B appear to have had a more negative experience. In room B, participants felt that the response time of the windows was too long and that the depth of tint was not sufficient to adequately control glare and reflections. When they experienced visual discomfort, they tended to use the blinds without trying the windows first. Satisfaction with the EC windows in room B was generally higher during the summer months than at other times of the year, and it was felt that there were fewer problems when solar altitude was high.

In both rooms, the zoning of the windows was felt to be a useful feature, as it allowed users to control individual zones separately, and because it meant that the upper and lower portions of the windows could have different control settings, so that the lower zones were less sensitive and tinted less often. The effect of the glazing tint on the appearance of colours and the view out was an important issue. Participants felt that the tinting sometimes made skin tones and colours in the room appear duller, could reduce their ability to judge weather conditions by looking through the window, and could distort their perception of the time of day. However, after the control system had been upgraded and configured so that the lower zones remained un-tinted more of the time, there were fewer comments about the distortion of colours in the room. This indicates

that the zoning of the windows reduced the impact of the EC glazing tint on the appearance of colours. This aspect is examined in more depth in Chapter 9.

The contrast in experience between the rooms echoes the pattern that was evident in the initial reactions of occupants during the first few months after the window retrofit. It is possible that the views established during this period continued to govern participants' attitudes towards the EC windows, and in addition a number of other factors may have been at play, such as furniture layout and social aspects. These are discussed in Chapter 10.

## **Chapter 8**

### **Occupant interaction with EC window controls and blinds**

In this chapter, the results of the observed data collection are described. This body of data is made up of the recorded actions of occupants as they interacted with the EC window manual controls and blinds in their offices. Given that these actions are likely to be in response to some perceived visual discomfort, these data can be used as a marker for times when occupants experienced visual discomfort because the EC window in automatic mode alone was not sufficient to meet their needs. Thus, the term “visual comfort action” is used to describe the use of manual EC window controls and blinds.

External daylight conditions and EC window state around the times of visual comfort action are studied, in order to understand what external conditions were likely to produce visual discomfort, and how the EC windows responded at such times. Internal lighting conditions around times of visual comfort action are also studied, using data from the HDR images, allowing possible links between measured luminance data and visual comfort behaviour to be explored. Lastly, an analysis of daily external daylight conditions and visual comfort actions is carried out. This allows further exploration of links between external conditions and the visual comfort control behaviour of occupants.

#### **8.1 Blind usage**

As explained in Chapter 5, blind usage data were collected using two methods: Photos of the external façade and a blinds diary in room B.

##### **8.1.1 Façade photos**

A series of photos of the façade were taken at random intervals between December 2013 and June 2014. By studying these images, the total proportion of glazing covered by a blind in each room was determined and expressed as percentage blind occlusion. An example is shown in Figure 8.1 and full details of this analysis can be found in Appendix VIII.





**Figure 8.1** A sample façade photo and associated blind occlusion.

Close visual inspection of the façade photos (*i.e.* zooming in on the digital images) allowed reflections on the outside of the windows to be distinguished from the presence of blinds in most cases. The size of the image shown in the figure does not allow for such distinctions; hence, the reflection on the small window of Room A could be mistaken for a blind, but it is not.

A total of 42 images were taken, however, nine of these could not be analysed because the blind positions were indeterminate due to reflections on the façade. From the remaining 33 images, the average blind occlusion was found to be 7% in room A and 46% in room B. This result is consistent with anecdotal evidence gathered on researcher visits to the rooms and feedback obtained through interviews (Chapter 7), which suggested that the occupants of room B lowered the blinds more frequently than those in room A.



### 8.1.2 Blinds diary

A blinds diary was completed by occupants during April 2013 – March 2014. One A4 diary sheet was mounted on the wall near the windows, and participants were asked to fill it in whenever they lowered the blinds. When the sheet was full, it was replaced with a new blank sheet. The sheets provide a record of the times when blinds had been lowered, along with some brief information about the reason for lowering the blinds. As explained in Chapter 5, blinds diary data are only available for room B.

An example of a completed blinds diary sheet is shown in Figure 8.2. Occupants' initials have been obscured to protect their identity. A total of 119 blinds diary entries were identified for analysis. The data were verified using HDR images taken around each entry time.

## BLINDS DIARY

Why did you lower the blinds?

Date	Time	Reason		
		Please enter the initials of the person affected		
				Other
5/12/13	11.00			
6/12/13	8.55			
10/12/13	10.45			
9/12/13	12.04			
9/12/13	12.35			
11/12/13	11.45			
12/12/13	9.00			
13/12/13	9.05			
13/12/13	12.10			
17/12/13	9.06			
17/12/13	10.45			
17/12/13	12.30			
18/12/13	8.55			
18/12/13	09.30			
19/12/13	09.10			
19/12/13	11.00			
20/12/13	09.07			
20/12/13	11.20			
21/1/14	09.10			
21/1/14	11.45			
3/1/14	09.10			
3/1/14	11.50			
6/1/14	8.55			
14/1/14	11.30			
7/1/14	10.30			
8/1/14	09.15			
8/1/14	12.00			



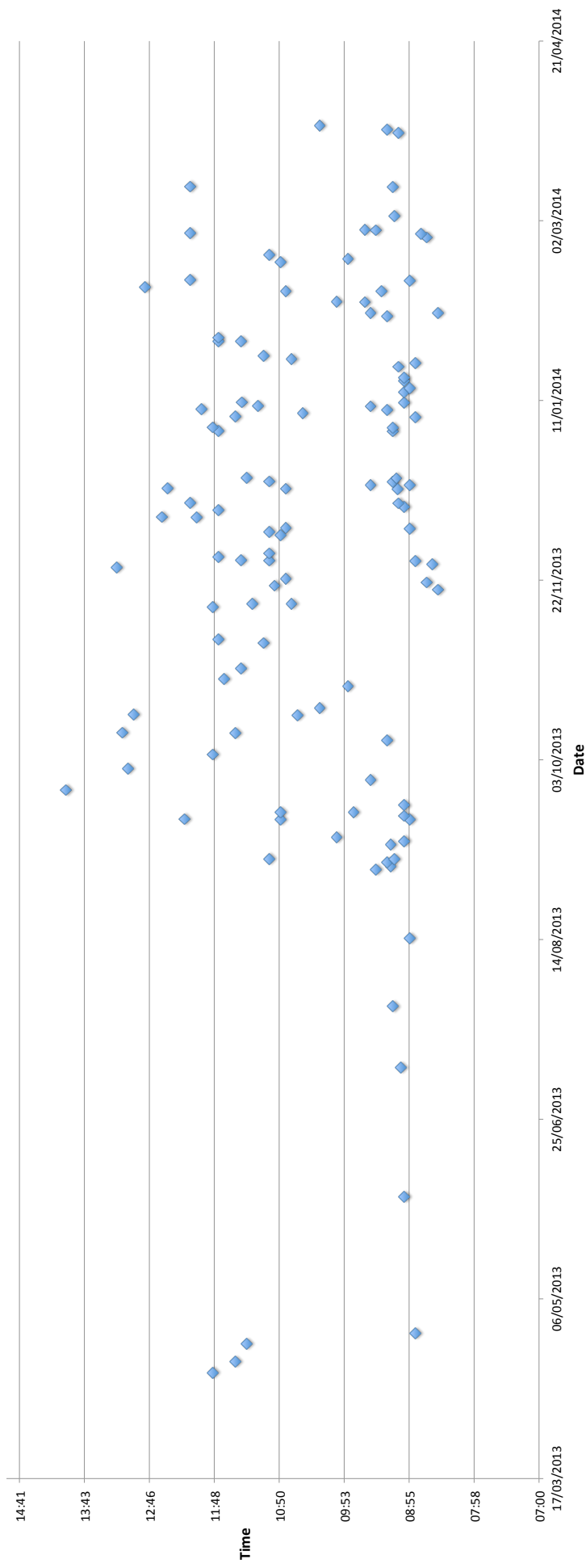
Key:  The sun is shining into the person's eyes  
 The sun is shining onto the person's computer screen

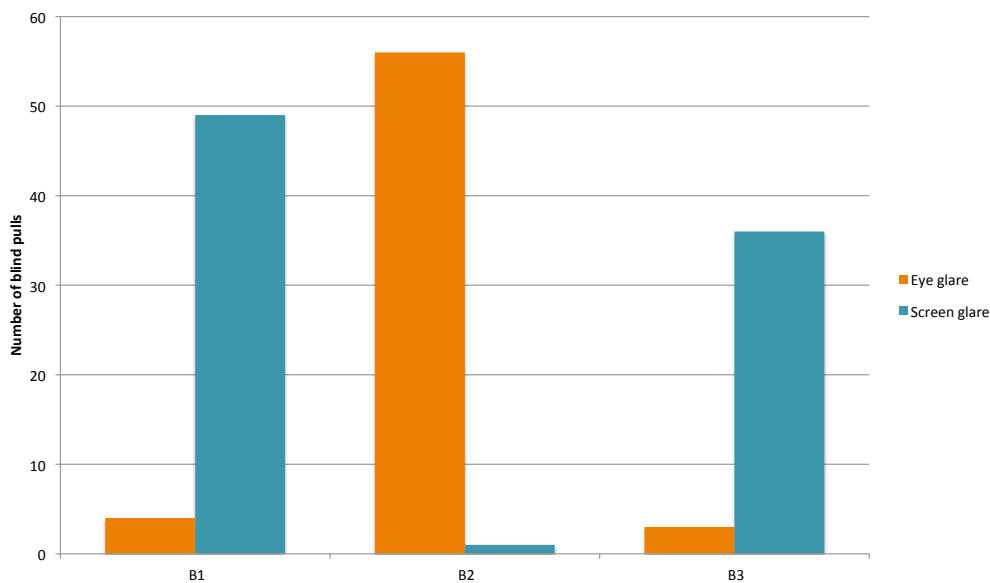
Figure 8.2 Example of a completed Blinds Diary

Figure 8.3 illustrates the blinds diary data, showing the times when blinds were lowered over the 11-month period, with date on the x-axis and time of day on the y-axis. It can be seen that there is a concentration of activity in the winter period, and that most of the entries were made between 09:00 and 12:00. This indicates that blinds were lowered more often when the solar altitude was lower and when the solar azimuth was such that the sun was shining onto the façade.

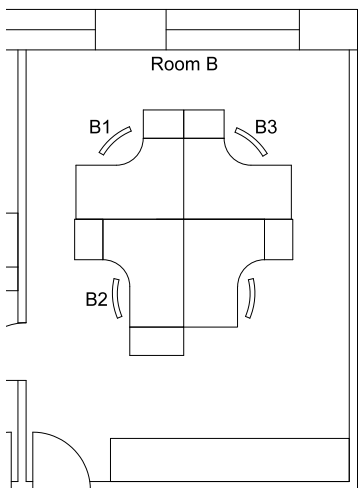


**Figure 8.3** Times when blinds were lowered in room B

In each blinds diary entry, occupants were asked to identify the person for whose benefit the blinds were being lowered, and whether it was to address screen reflections or direct eye glare. Entries were relatively evenly distributed across the three participants in room B. Figure 8.4 shows the type of glare that each participant indicated was being addressed when they made an entry in the blinds diary.



**Figure 8.4** The type of glare being addressed by each participant when lowering blinds



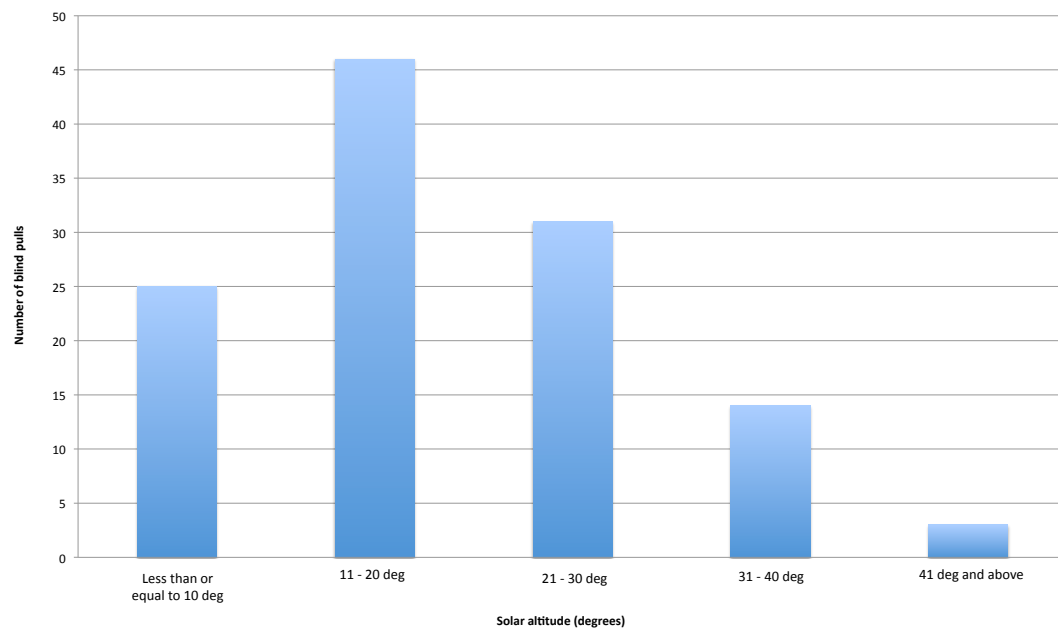
**Figure 8.5** Room B desk layout

It can be seen that the vast majority of actions taken by participant B2 were to deal with direct eye glare, whilst for the other two participants it was largely screen glare that was being addressed. Considering the layout of room B, these results are expected (Figure 8.5). Participant B1 and B3 both sit with their backs at least partly to the windows, whilst participant B2 has a view of the windows.

## 8.2 Conditions at times of blind use

### 8.2.1 Sun position

It was seen in Figure 8.3 that blind-lowering activity increased during times of low solar altitude (*i.e.* the winter months). This is illustrated further in Figure 8.6, below, which shows the relationship between solar altitude and the number of times blinds were lowered.



**Figure 8.6** Solar altitude when blinds were lowered

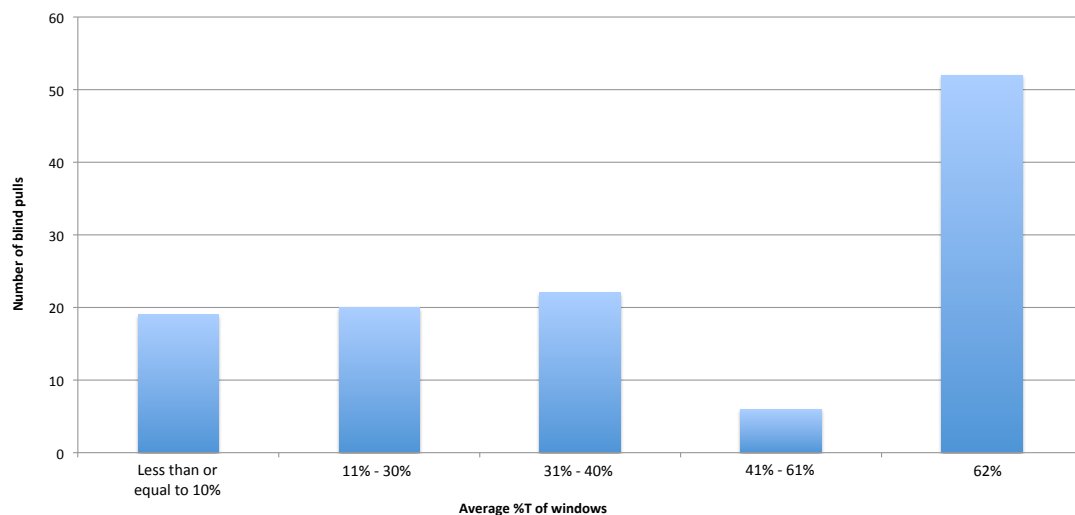
It can be seen that most blind-lowering activity occurred at times when the solar altitude was between 11° and 20°. Less blind usage occurred when the solar altitude was below 10°; this is probably because at these very low altitudes, the sun was hidden behind buildings on the opposite side of the street.

### 8.2.2 EC window state & façade illuminance

To investigate external conditions at the times when occupants lowered the blinds (and thus were presumably experiencing visual discomfort), the EC window condition and façade illuminance around the times when blinds were lowered were identified from the EC window control system log. This analysis

relates to room B only, since detailed blind usage data are not available for room A, as explained previously.

As the windows are made up of several zones, each of which can have a different transmittance at a given time, the area-weighted average transmittance of all the windows in the room was determined in each case. Figure 8.7 shows the average transmittance of the windows in room B at the times when blinds were lowered (*i.e.* to the nearest minute, as indicated by the time given on the blinds diary). It should be noted that in over 50 cases (42% of total), the windows were completely un-tinted (*i.e.* with an average transmittance of 62%) at the times when the blinds were lowered.

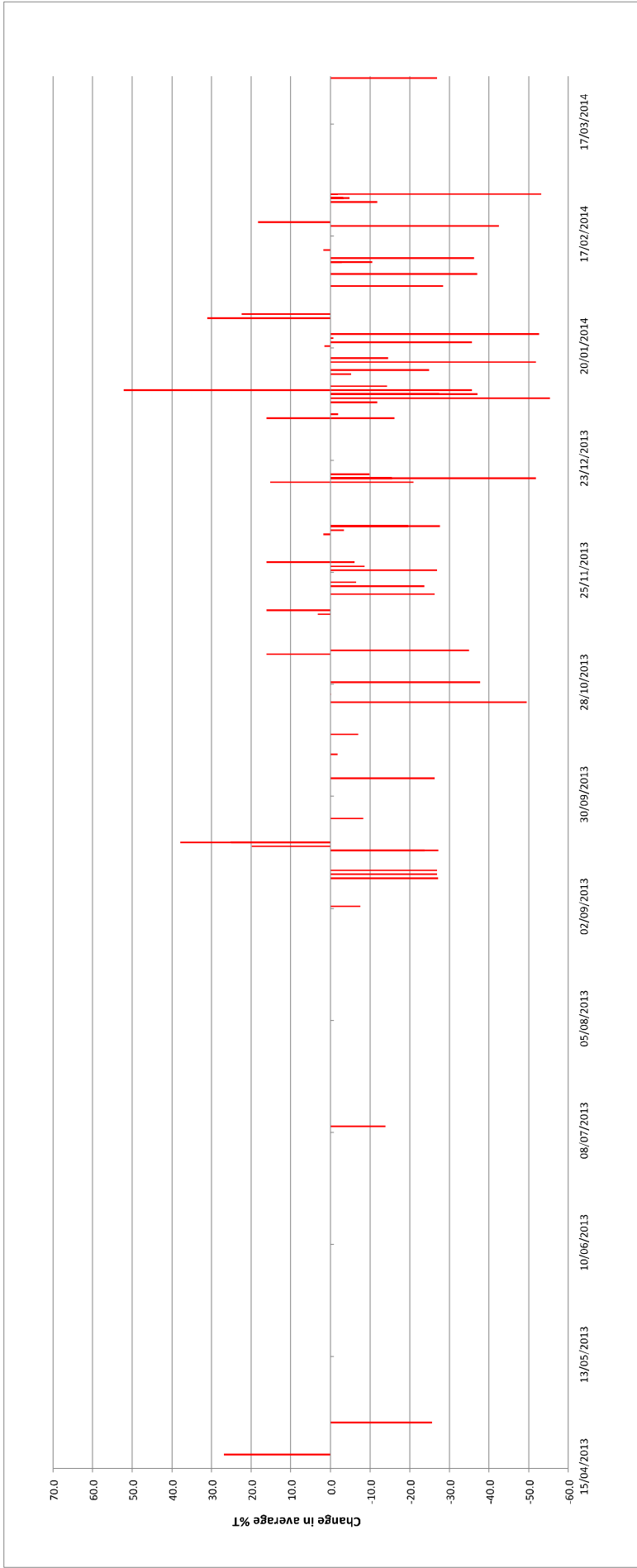


**Figure 8.7 Ave. transmittance (%T) of windows in room B when blinds were lowered**

The large proportion of cases in which the EC windows were not tinted at all when blinds were lowered suggests a possible disconnect between EC window control system calibration and the visual comfort needs of occupants. That is, the EC window control system did not see conditions that warranted tinting of the glass, whilst the occupants were motivated to lower the blinds, presumably because they were experiencing visual discomfort. Whilst it is possible that the blinds were sometimes lowered for some arbitrary reason (*i.e.* other than to deal with glare), it is also possible that the EC window control system was in fact about to increase tinting when occupants lowered the blinds. In this way, the

occupants in room B may have been essentially “overriding” the EC window control system (albeit by lowering the blinds instead of using the manual window controls). To investigate this, the window condition 10 minutes after the blinds were lowered was examined.

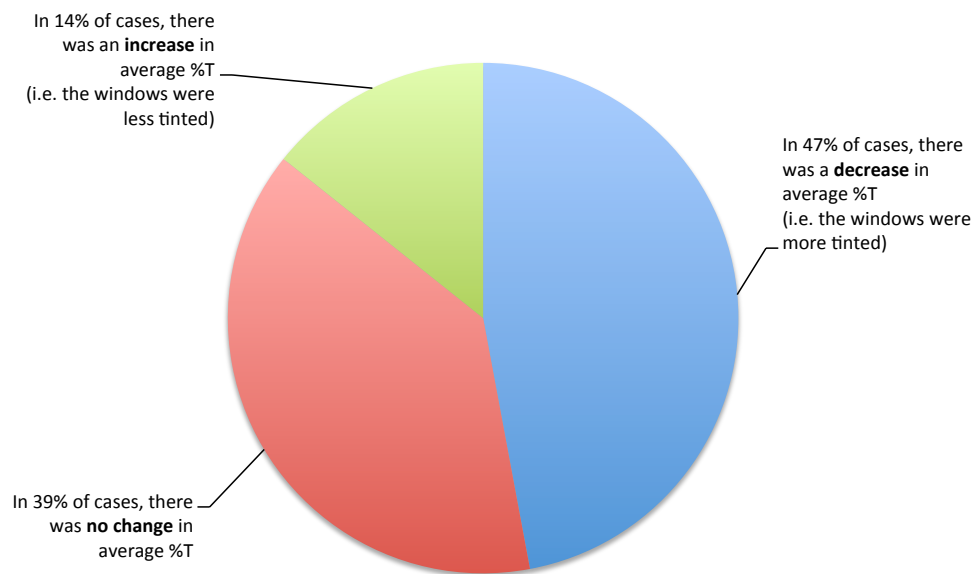
Figure 8.8 shows the change in average transmittance 10 minutes after the blinds were lowered. The red vertical lines indicate the change in transmittance, with lines above the x-axis indicating an increase and lines below indicating a decrease. The heights of the lines indicate the magnitude of change. It can be seen that, in a considerable number of cases, there was a reduction in average transmittance. This supports the idea that the window control system was about to increase tinting in many of the cases when blinds were lowered.



**Figure 8.8** Change in average transmittance of the window in room B 10 minutes after the blinds were lowered. Vertical red lines above the x-axis represent cases where transmittance increased (*i.e.* the windows were less tinted), whilst those below the x-axis indicate cases where it decreased (*i.e.* the windows were more tinted). The heights of the lines indicate the magnitude of change.



Figure 8.9 gives more detail about how the transmittance had changed 10 minutes after the blinds were lowered. It can be seen here that in almost half of cases, there was a reduction in transmittance, but also that in a sizeable proportion of cases (39%), there was no change in transmittance. In the small number of remaining cases, there was actually an increase in transmittance.

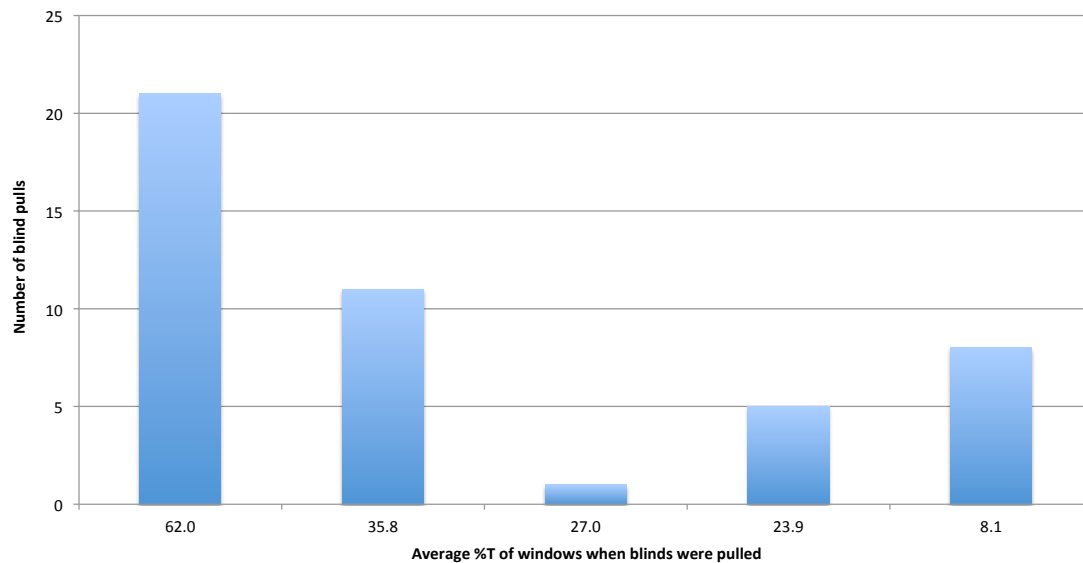


**Figure 8.9 Breakdown of changes in average transmittance of windows 10 minutes after blinds were lowered**

The cases where there was no change or an increase in transmittance are interesting, because they signify occasions when the visual comfort needs of the occupants appeared at odds with the EC control system protocol. That is, the control system did not consider that an increase in tinting was required, and in some cases even determined that a decrease in tinting was needed, whilst the occupants called for more shading by lowering the blinds. Hence, it is valuable to look in more detail at these cases, since they can give some insights into the limits of the EC window control system in meeting the visual comfort needs of occupants.

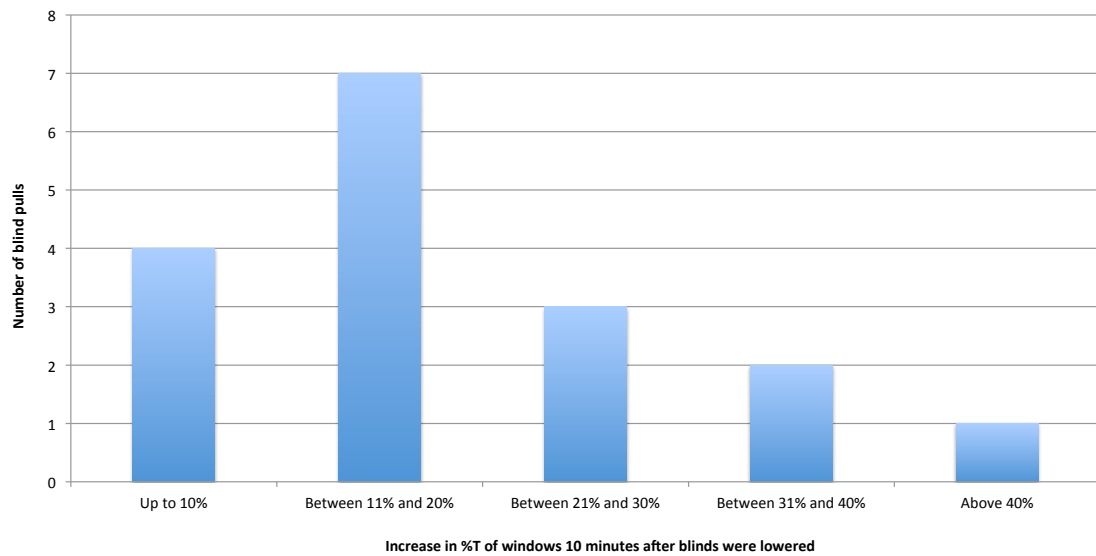
*Looking in more detail at the “no change in %T” and “increase in %T” cases*

Figure 8.10 shows the average transmittance of the windows at the times when the blinds were lowered in the “no change” cases. It can be seen that in a significant number of these cases, the glazing had been un-tinted (average %T = 62%) and remained so 10 minutes after the blinds were lowered.



**Figure 8.10** Average transmittance of windows when blinds were lowered in cases where there was no change in %T after 10 minutes

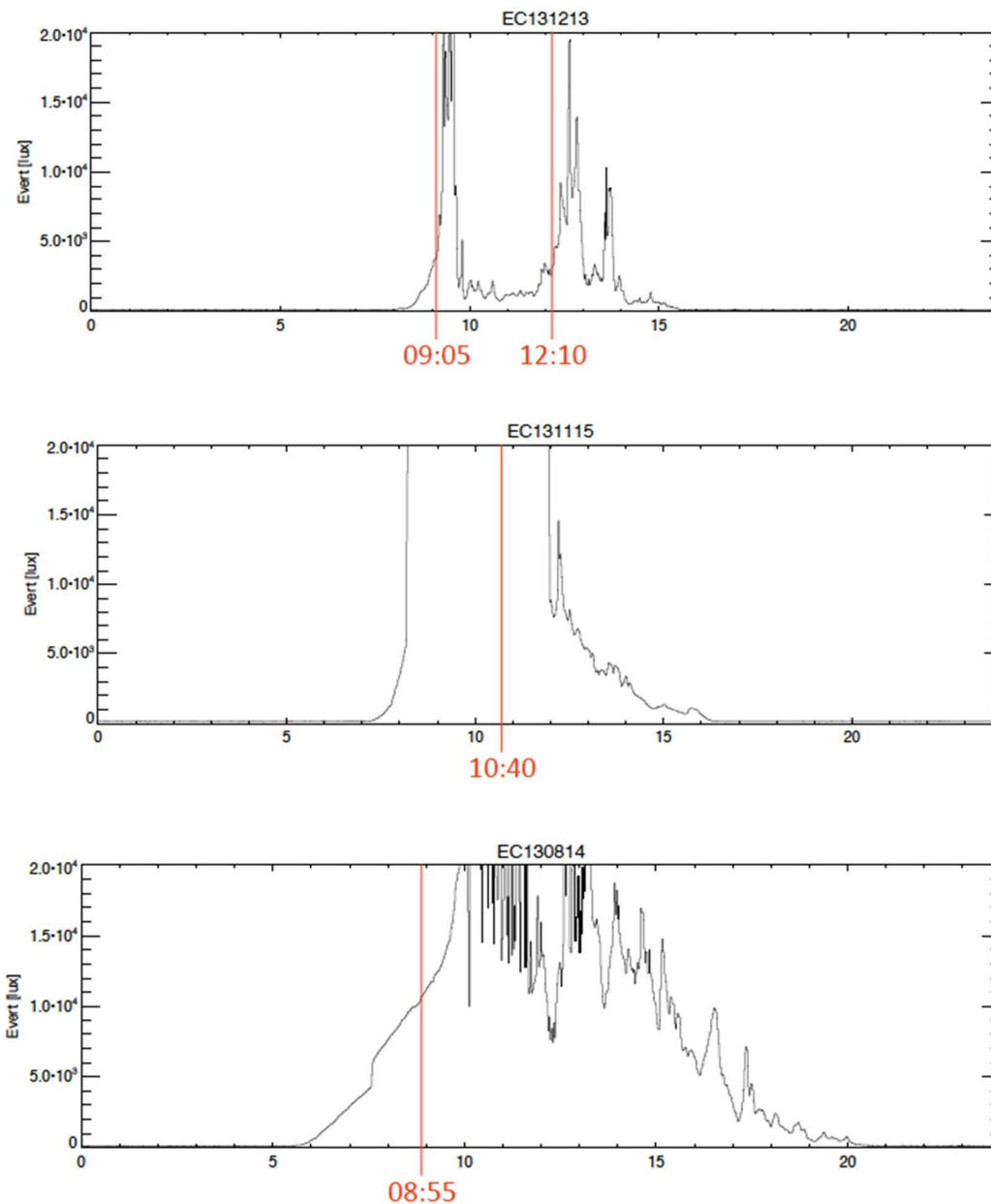
Figure 8.11 shows how the average transmittance increased 10 minutes after the blinds were lowered in the “increase in %T” cases. Although this involves a smaller number of cases, the fact that the control system determined that a decrease in tint level was required, despite occupants lowering the blinds, suggests that these cases are worthy of further investigation.



**Figure 8.11 Increase in average transmittance of the windows 10 minutes after blinds were lowered in cases where there was an increase in %T after 10 minutes**

These apparent anomalies could be explained by the weather conditions at these times. Given the non-instantaneous response of the EC window system, it is possible that a brief glare condition occurred that was severe enough to motivate an occupant to lower the blinds, but did not last long enough to trigger a response in the EC control system, *i.e.* a “spike” in the exterior sensor reading.

To investigate this theory, the exterior sensor data (façade illuminance) around the times when the blinds were lowered were studied. The analysis found that in a large proportion of the “no change” cases (26 of 44), there was a spike in the profile at around the time when blinds were pulled. In 12 cases, the blinds were lowered during a period of continuously high sensor readings. In the small number of remaining cases, the blinds were lowered at a time when the sensor reading was relatively low, although gradually increasing. This analysis of the “no change” cases suggests that, in general, the blinds were lowered at a time when the sensor reading was at or approaching its maximum reading (saturation point) of 81 klux. Figure 8.12 illustrates typical examples of these three scenarios. The graphs for all cases can be found in Appendix IX.



**Figure 8.12** Three typical examples of exterior sensor behaviour around the time when the blinds were lowered in the “no change” cases

**Top:** Blinds lowered around the time of a spike in the exterior sensor reading.

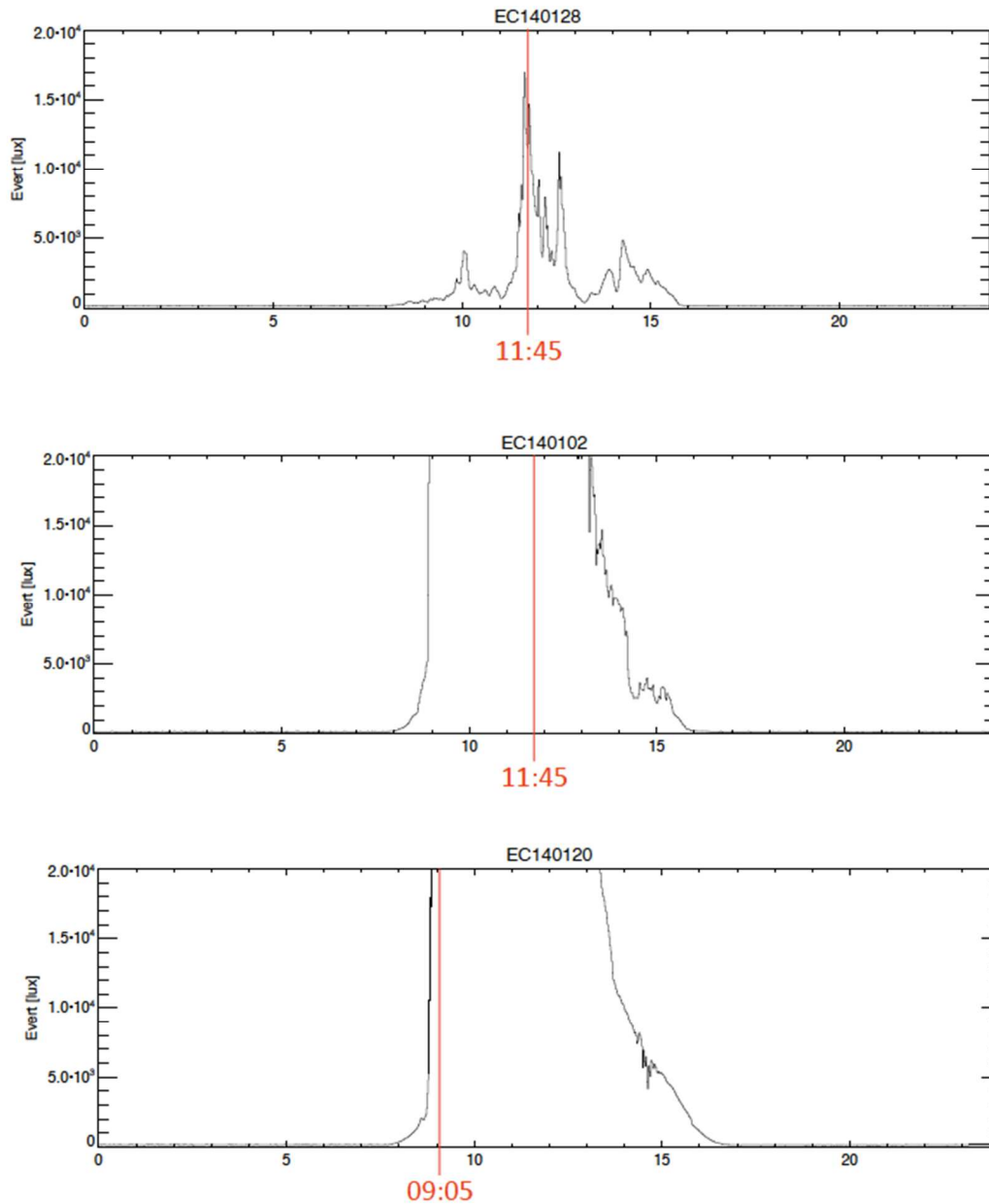
**Middle:** Blinds lowered during a period of continuously high exterior sensor reading.

**Bottom:** Blinds lowered at a time when the exterior sensor reading was relatively low but gradually increasing.

In 26 of the 44 “no change” cases, the sensor reading was undergoing rapid fluctuation at the times when the blinds were lowered. This supports the hypothesis that in many of these cases, a spike in the façade illuminance

occurred that motivated an occupant to lower the blinds, but was not prolonged enough to trigger the tinting of the EC windows (Figure 8.12, top). In a smaller number of cases (12), the blinds were lowered when the façade illuminance had already been high for some time (Figure 8.12, middle). Such high sensor readings would have triggered the control system to fully tint the upper panes and to tint the lower panes to some extent. The fact that an occupant chose to lower the blinds in these circumstances suggests that they were still uncomfortable even with the EC windows fully tinted. The timing of the blind lowering is also of interest, since it occurs in the middle of this period of high façade illuminance, suggesting that the position of the sun became critical for an occupant at that time, or for some other reason, such as an occupant having been out of the room and then returning. In a small number of cases (6), the sensor readings were consistent with cloudy skies and yet the blinds were still lowered. These seemingly arbitrary blind-pulls could be examples of habitual blind use, especially since they tended to occur at around the same time of day, at around 09:00 (Figure 8.12, bottom), the start of the working day for many occupants.

In a similar way to the “no change” cases, the façade illuminance sensor profiles were examined to investigate whether a spike in the sensor reading could explain the “increase in %T” cases. The analysis found that, of the 16 cases, nine were characterised by a rapid increase in the exterior sensor reading followed by a sustained decrease around the time the blinds were lowered. In many cases, the exterior sensor reading was fluctuating throughout the day, and particularly around the time the blind was lowered. A typical example of this is shown in Figure 8.13 (top). In the remaining cases, the sensor reading is either at a sustained high level before and after the blinds are pulled (three cases), or there is a sharp increase before the blind pull, followed by a sustained high reading (four cases). Figure 8.13, middle and bottom respectively, show typical examples of these. The graphs for all these cases can be found in Appendix X.



**Figure 8.13** Three typical examples of exterior sensor reading around the time when the blinds were lowered in the “increase in %T” cases.

**Top:** Blinds lowered around the time of a sharp increase in the exterior sensor reading followed by a sustained decrease.

**Middle:** Blinds lowered during a period of continuously high exterior sensor reading.

**Bottom:** Blinds lowered around the time of a sharp increase in exterior sensor reading followed by a sustained high reading.

In the majority of the “increase in %T” cases, the blinds were lowered at a time when there was a spike in the sensor reading followed by a sustained decrease. This suggests that these cases can be explained by a spike in the façade illuminance that was severe enough to motivate an occupant to lower the blinds, but was not prolonged enough to trigger the tinting of the EC windows, followed by a decrease of exterior illuminance that was sustained enough for the control system to trigger an increase in %T. In other words, these cases, like the “no change in %T” cases, can be largely explained by fluctuating facade illuminance around the time the blinds were lowered.

In the remaining “increase in %T” cases, the sensor reading is either at a sustained high level before and after the blinds are pulled, or there is a sharp increase before the blind pull, followed by a sustained high reading. It does not make sense that the EC window control system should increase transmittance under such conditions. It is possible that a manual override was made that requested a higher transmittance, however, considering that an occupant in the same room had recently lowered the blinds, this is very unlikely, or at least illogical. It is also possible that in these cases the blinds were lowered for some other, unknown, reason.

### **8.2.3 Internal conditions (HDR metrics)**

The internal luminous conditions around the times when blinds were lowered, as described by HDR-derived metrics, were examined to explore the relationship between observed visual comfort actions and measured lighting conditions. Given that visual comfort actions are indicative of visual discomfort, this analysis addresses the deeper question of whether the data collected in this study can show a link between measured conditions and occupant experience. As there was one HDR camera located in room A for only limited periods, insufficient HDR data were generated from room A to enable a useful analysis to be undertaken. Since most of the manual overrides occurred in room A, whilst in room B the blinds were frequently used, this analysis only relates to internal conditions in room B around the times when blinds were lowered.

For each entry in the blinds diary, the chronologically closest HDR images (*i.e.* within a maximum of 15 minutes), taken before and after blinds were lowered, were identified. Eight luminance metrics, as described in Chapter 5, were extracted from these images. Images generated by both cameras HDR1 and HDR2 were analysed (the camera locations are shown in Figure 5.4). Hence, for each blinds diary entry, there were four associated HDR images: One before and after a blind was lowered, and one for each camera. Time series plots for every blind use were produced for the following parameters:

- Min luminance (Min L)
- Maximum luminance (Max L)
- Mean luminance (Mean L)
- Median luminance (Median L)
- Standard deviation luminance (Std Dev L)
- Ratio of 75<sup>th</sup> to 25<sup>th</sup> percentile luminance (75:25)

In addition, two further plots were produced:

- The mean luminance in the front (window) half of the room against that of the rear half of the room (Mean L H1 v. Mean L H2)
- Minimum luminance against maximum luminance (Min L v. Max L)

This analysis sought to establish whether any of the chosen HDR metrics could be used as a proxy for visual discomfort or visual comfort, on the basis that HDR metrics derived from images taken before blinds were lowered described a visual discomfort condition, and images taken after blinds were lowered described a visually (more) comfortable condition. It was expected that changes in luminous conditions brought about by the lowering of the blinds would be evident from the plots derived from images taken before and after blinds were lowered.

A selection of graphs is shown in Figures 8.14 (camera HDR1) and 8.15 (camera HDR2); the complete set of graphs can be found in Appendix XI. Several of the time series plots suggest a cyclical variation over the data collection period, in



concert with solar altitude. There were generally fewer points in the summer months because the blinds were lowered less during these times.

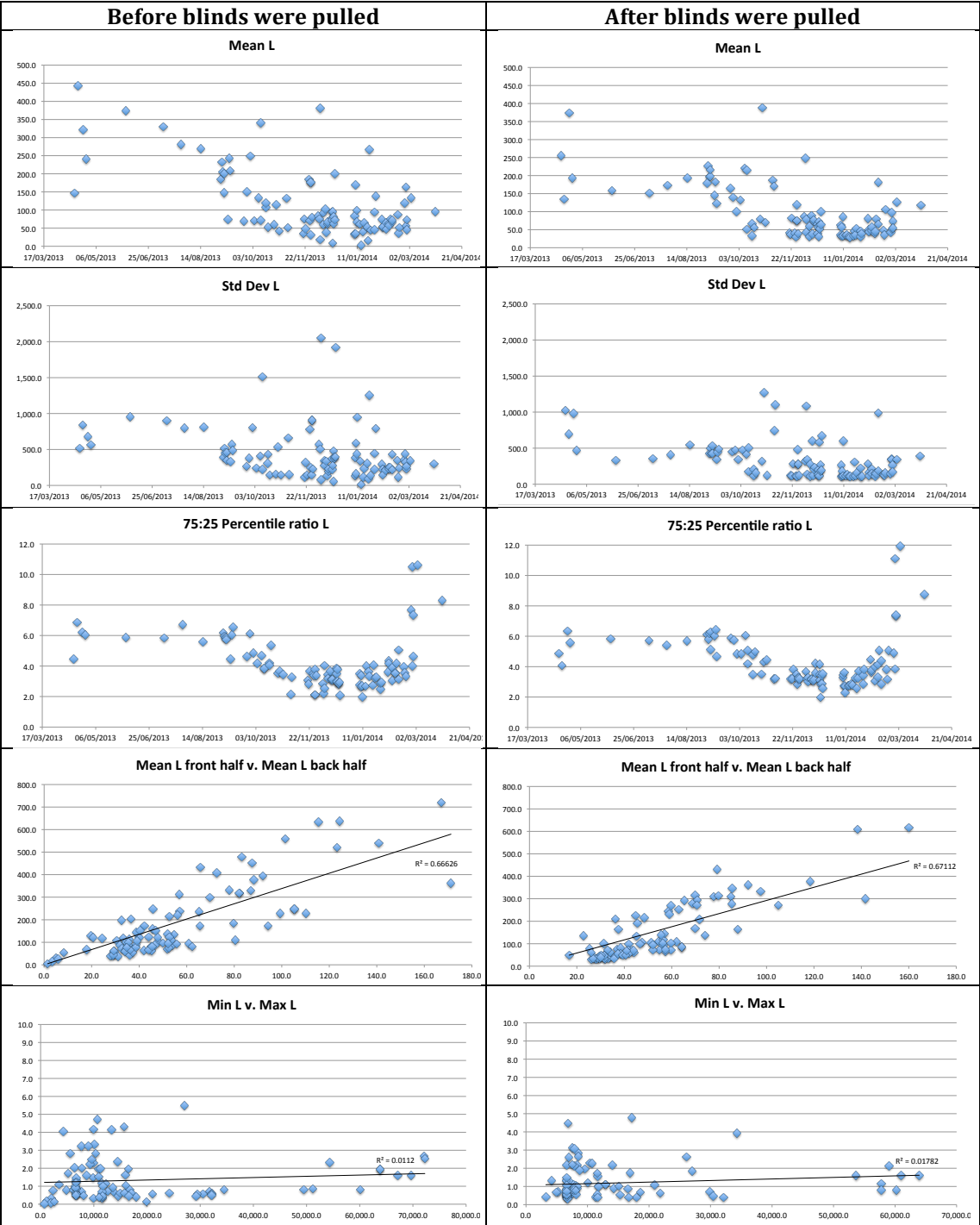


Figure 8.14 Selected luminance metric graphs for camera HDR1



**Figure 8.15** Selected luminance metric graphs for camera HDR2

The metrics that appeared to vary with solar altitude were Min L, Mean L, Median L, and 75:25 percentile ratio. These were plotted against solar altitude to investigate the relationship further. Table 8.1 provides a summary of the  $R^2$  values in each case; the graphs can be found in Appendix XI. The results suggest

a correlation between 75:25 percentile ratio from camera HDR2 and solar altitude, and a weak relationship between the other luminance metrics and solar altitude.

**Table 8.1 Summary of  $R^2$  values for selected luminance metrics v. solar altitude**

Camera	Metric	Before blinds	After blinds
HDR1	Min L	0.33	0.31
	Mean L	0.36	0.39
	Median L	0.26	0.23
	75:25 L	0.21	0.23
HDR2	Min L	0.07	0.12
	Mean L	0.27	0.27
	Median L	0.25	0.27
	75:25 L	0.62	0.60

From Figure 8.14 and 8.15, it can be seen that the Mean L H1 v H2 plots indicate a moderately strong linear proportional relationship between the mean luminance of the front (window) half and that of the rear half of the room, with  $R^2$  values of between 0.66 and 0.75. It can be seen that the slope of the line slightly decreases after the blinds were lowered, indicating that the lowering of blinds reduces the difference between the mean luminance in the front and rear half of the room, which is as expected. Thus, this relationship appears to be more clearly linked to visual comfort behaviour than the others investigated in this analysis. However, the change in the relationship between these two variables only undergoes a modest change after the blinds were lowered.

The Min L v Max L plots indicate a weak linear relationship between these two variables. It was expected that these variables would correlate more strongly, and would undergo a more obvious change after blinds were lowered, reflecting the reduction in the range of luminances in the space brought about by lowering the blinds, *e.g.* that the maximum luminance after the blinds were lowered would generally decrease. However, it was found that in almost half of cases the

maximum luminance actually increased after the blinds were lowered. There are two possible reasons why these metrics did not change as expected after the blinds were lowered:

- (a) The blinds may have been only partly lowered, resulting in a sunlight patch or bright piece of sky still visible in the “after blinds” image.
- (b) Due to the 30-minute interval between HDR image captures, the “before blinds” image may not have captured the conditions that caused discomfort and motivated the lowering of blinds. This is particularly likely if the façade illuminance was fluctuating at the time.

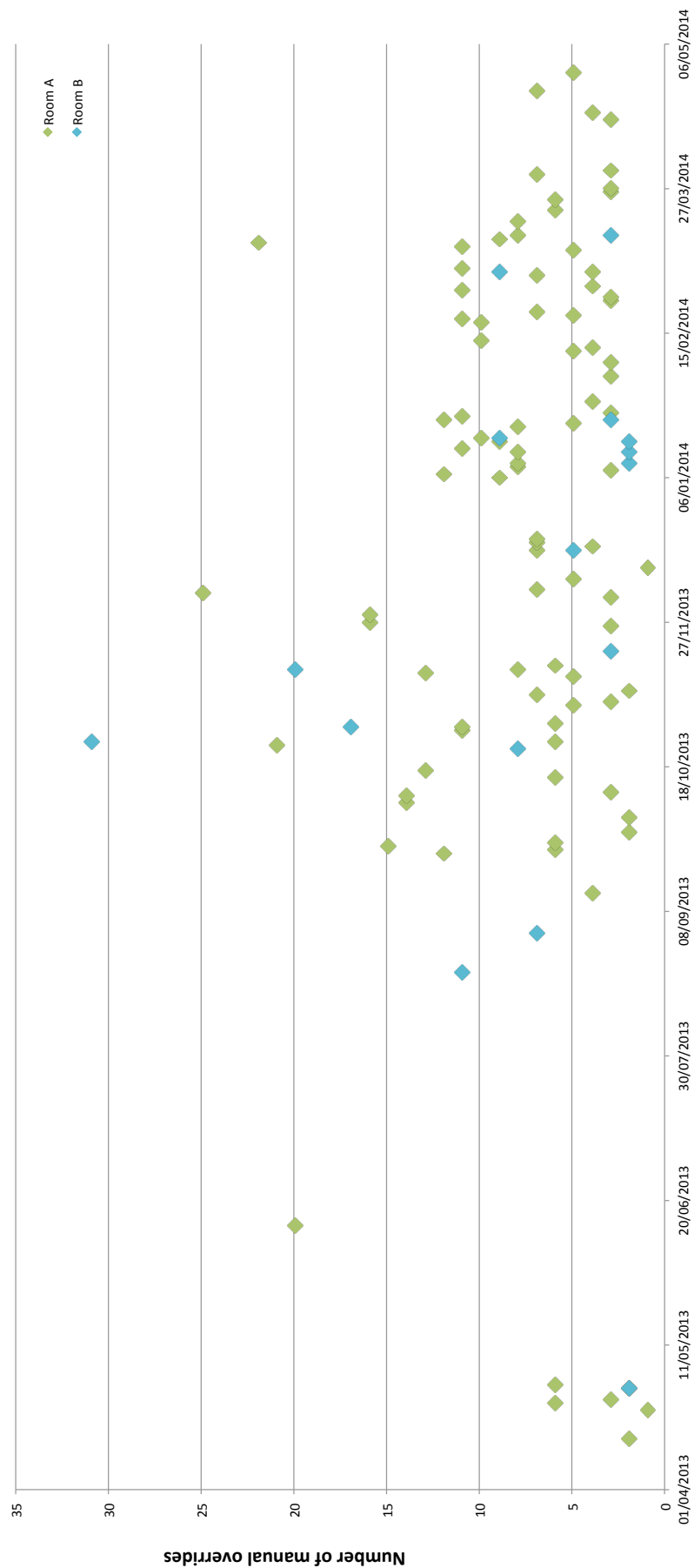
The influence of daylight linked electric lighting was also considered, given that this system would increase light output when blinds were lowered to compensate for the loss of daylight. However, it was found that the luminance levels produced by the light fittings were relatively low compared with those created by direct sunlight in the room, and thus could not have significantly affected the results.

### **8.3 EC manual window controls usage (manual overrides)**

Detailed information about occupants’ interactions with the EC window manual controls was available from the control system log from 11<sup>th</sup> April 2013 onwards. Just over 12 months’ data are included in this analysis, from 11<sup>th</sup> April 2013 – 30<sup>th</sup> April 2014. Each time a switch was pressed by an occupant (*i.e.* a manual override), the following information was recorded:

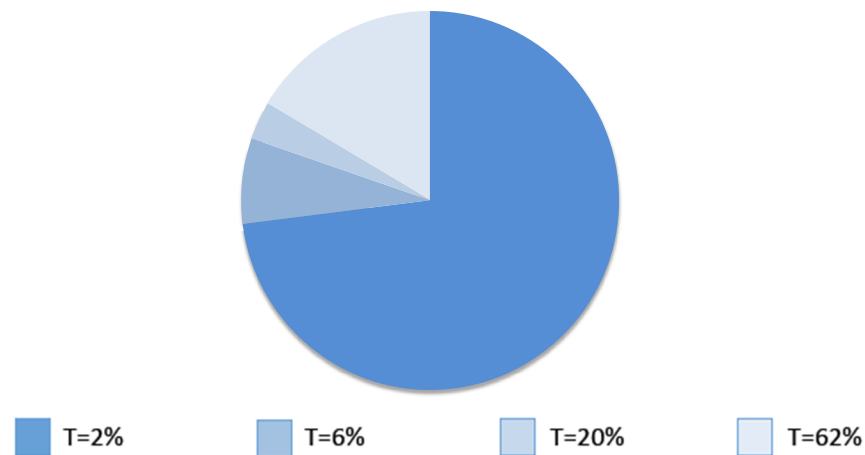
- Time the switch was pressed
- Which switch was pressed (*i.e.* zone)
- Number of times the switch was pressed
- Target transmittance (%T) of the switch action

Figure 8.16 shows a time series of manual overrides in each room over the data collection period. It can be seen that there is an increase in activity during the winter and a decrease during the summer months, suggesting that more manual overrides occurred during periods of low solar altitude. It can also be seen that there were many more manual overrides in room A than in room B.



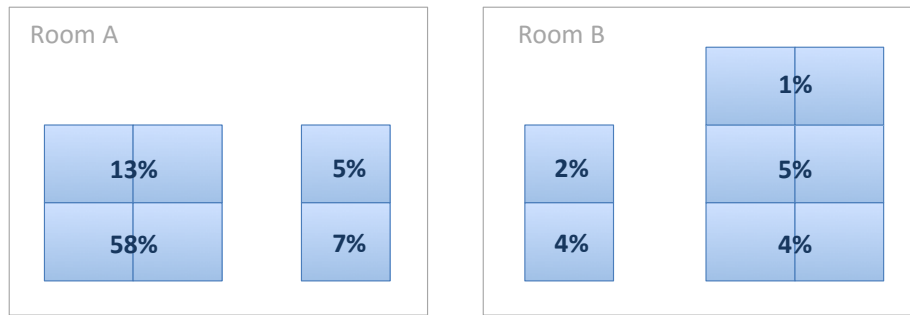
**Figure 8.16** Number of manual overrides in each room over the data collection period

Figure 8.17 shows a breakdown of the all the manual overrides that occurred in the data collection period by target transmittance value. The vast majority (73%) of manual overrides were to fully tint the window zone (target  $T = 2\%$ ), whilst 16% of manual overrides were to un-tint the window zone (target  $T = 62\%$ ). Relatively small numbers of manual overrides targeted an intermediate level of tint ( $T = 6\%$  or  $20\%$ ).



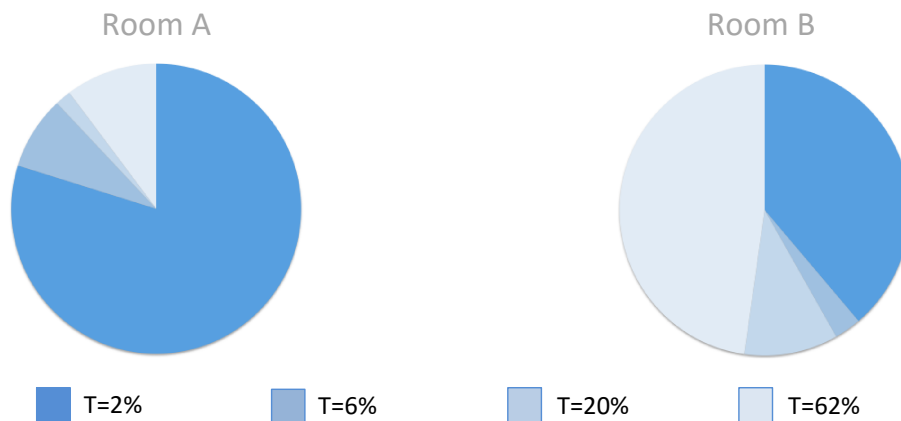
**Figure 8.17 Breakdown of all manual overrides by target transmittance (%T)**

As shown in Figure 8.16, there were significantly fewer manual overrides in room B compared with room A. Over the data collection period, there were 674 manual overrides in room A, but only 134 in room B; a five-fold difference between the two rooms. There was also a noticeable difference in both the target transmittance values and the distribution of manual overrides across window zones. Figure 8.18 shows the number of manual overrides across each window control zone during the 12-month data collection period. It can be seen that almost two-thirds of all manual overrides occurred in Zone 2 (the lower half of the large window in room A).



**Figure 8.18** Manual overrides in each zone as a percentage of the total number that occurred during the data collection period

Figure 8.19 gives a breakdown of manual overrides by target transmittance for each room. This shows that in room A, the vast majority of manual overrides were to fully tint the window, whilst in room B, almost half of the manual overrides were to untint the window (*i.e.* target  $T=62\%$ ).

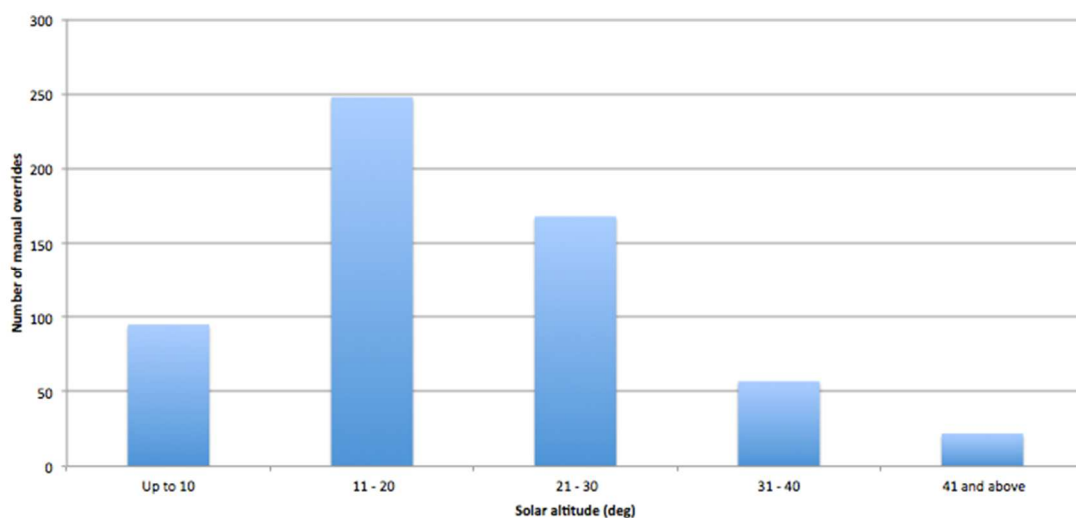


**Figure 8.19** Manual overrides by target transmittance (%T) for each room

## 8.4 Conditions at times of manual override

### 8.4.1 Sun position

In Figure 8.20, the full tint manual overrides only (*i.e.* those that had a target T of 2%) are plotted against solar altitude. The results suggest that manual overrides have a similar relationship with solar altitude to that of blind usage (Figure 8.6). The majority of full tint manual overrides occurred when solar altitude was between 11° and 20°. As with blind usage, the lower number of actions at solar altitudes below 10° can be explained by the fact that the sun was hidden behind neighbouring buildings at these very low altitudes.



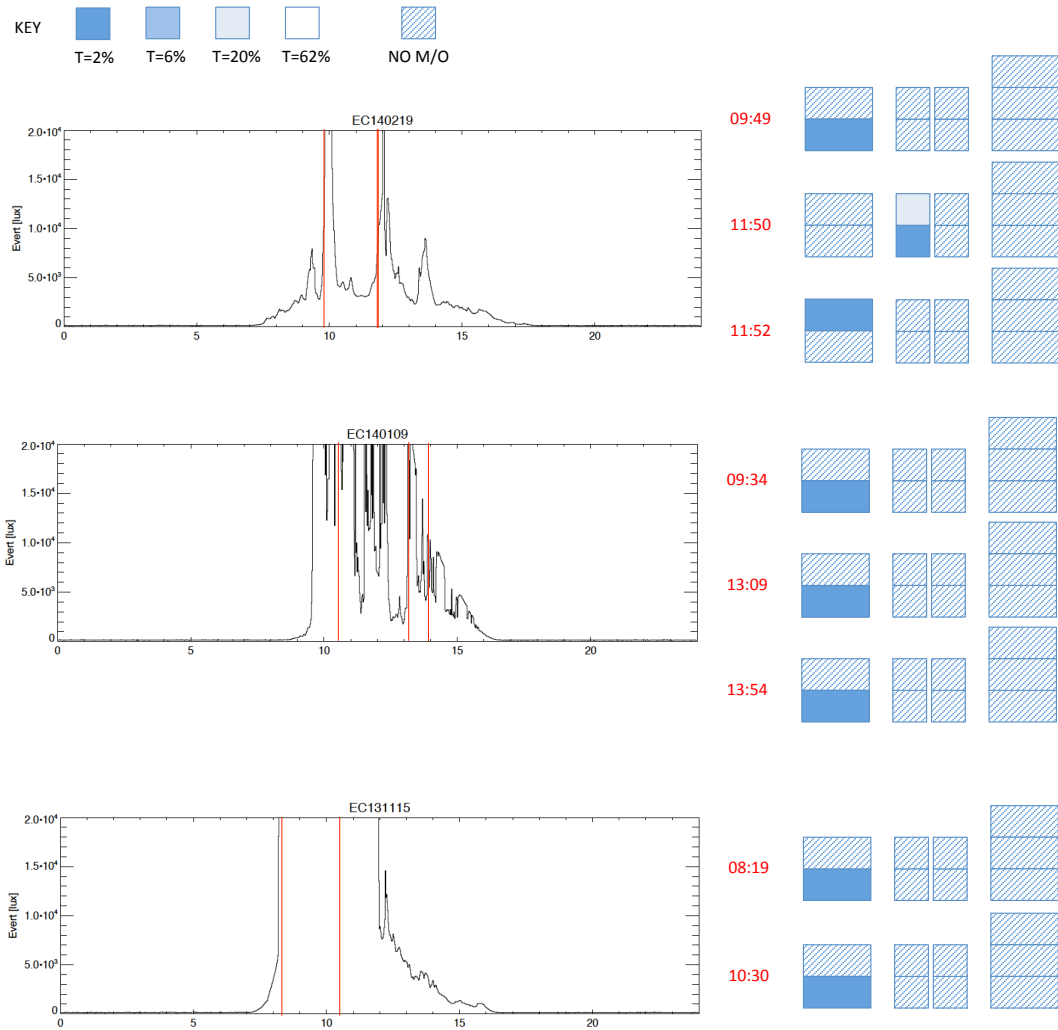
**Figure 8.20** Number of full tint (T = 2%) manual overrides at different solar altitudes

### 8.4.2 Façade illuminance

In the previous section, it was seen that in many cases, blinds were lowered at times when the exterior façade illuminance was in a state of flux, due to changeable weather conditions (*e.g.* fast-moving cloud across the sun). It is instructive to investigate whether a similar pattern can be found at times when manual overrides occurred.

The external façade sensor profiles were superimposed with manual override times and details (*i.e.* zone and target %T), some examples of which are shown in Figure 8.21. The analysis of all profiles can be found in Appendix XII.





**Figure 8.21** Three typical examples of façade illuminance sensor reading on days when manual overrides occurred.

Manual overrides are indicated by red vertical lines. The diagrams on the right hand side indicate the time of each manual override, the zone in which the manual override occurred, and the target transmittance (refer to the key at the top of the figure).

**Top:** Manual overrides coincide with distinct spikes in the sensor reading.

**Middle:** Manual overrides during a time of rapid fluctuation in the sensor reading.

**Bottom:** Manual overrides during a time of sustained high sensor readings.

It was found that in almost 20% of cases, manual overrides could be clearly linked to distinct spikes in façade illuminance (Figure 8.21, top). In another 35% of cases, manual overrides occurred in the midst of many spikes close together, *i.e.* rapidly fluctuating façade illuminance (Figure 8.21, middle). In around 30% of cases, the façade illuminance was stable but high when manual overrides

occurred (Figure 8.21, bottom). In this latter type, the first manual override typically occurred at around 8.30, at the beginning of the working day, and was followed by another around 2.5 hours later. In other words, the occupant essentially re-overrides the system after it reverts back to automatic after two hours. The remaining cases were either manual overrides with a target of  $T=62\%$  (*i.e.* to un-tint the glazing), or did not fall into any of the three categories described above. It is likely that at least some of these manual overrides were targeting an increase in transmittance, *e.g.* going from 6% to 20%.

Hence, the results of this analysis suggest that around half of manual overrides during the data collection period (intended to tint the window) occurred around times of fluctuating façade illuminance.

## **8.5 Combined visual comfort behaviour**

### **8.5.1 Visual comfort actions**

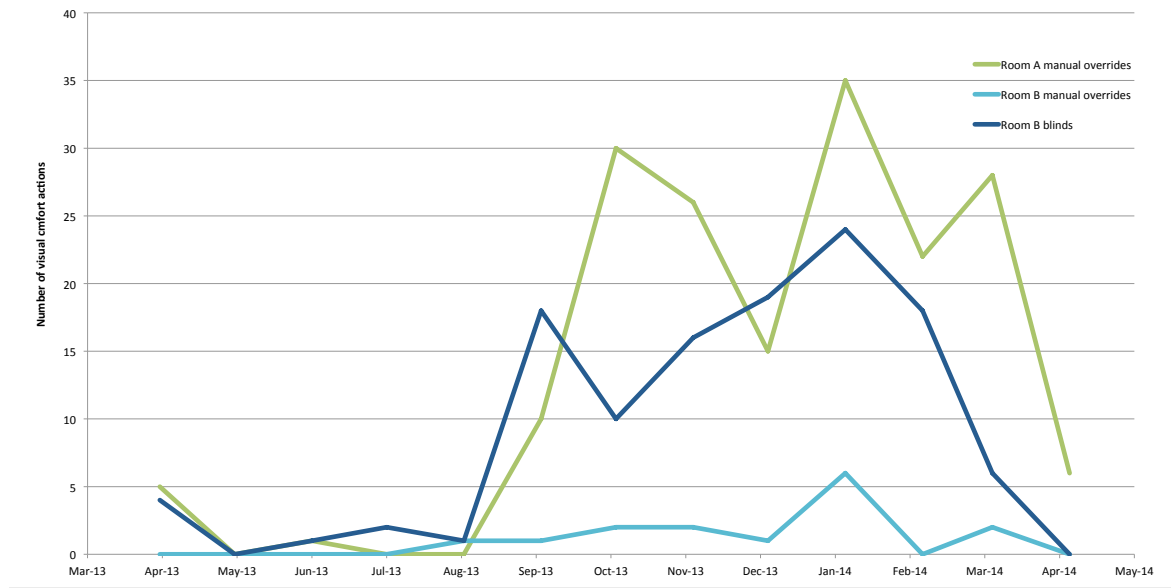
In this study, the observed actions of occupants as they tinted the EC window or lowered the blinds, presumably in response to visual discomfort, are termed “visual comfort behaviour”. It has been seen from the observed data that typically, visual comfort behaviour in the two rooms was substantially different, suggesting that the occupants of the two rooms generally addressed visual discomfort differently. In room A, the tendency was to use the EC window manual controls, whilst in room B it was to use the blinds. This supports the findings of the self-reported data, and in particular the interview data, which suggested a lack of engagement with the EC window controls in room B.

To explore this further, it is useful to look at all visual comfort behaviour data in combination. However, combining blind use data and manual override data is not straightforward because of the differences in the nature of the data sets. The blinds data are binary, *i.e.* the blinds were lowered or they were not lowered. The manual override data, however, consist of both binary data (manual controls were used, or they were not used) and quantitative data, because each button press was registered by the control system. Users often pressed a button multiple times, possibly in a non-rational attempt to achieve a faster response

from the system. This is typical of interactions with systems that cannot respond to a request immediately, *e.g.* pedestrian crossings and lift call buttons. As a result, there is a wide range in the number of manual overrides (button presses) per day: during the data collection period, the lowest number of manual overrides recorded in a room on a given day was one, and the maximum was 31. On days with higher numbers of manual overrides, they typically appeared in clusters, corresponding to the multiple button presses involved in a single action.

To overcome the disparity in the nature of the two data sets, the concept of “visual comfort action” is used. For the observed data collected in this study, a visual comfort action can be either an instance of lowering a blind or a cluster of manual overrides in a particular window zone with the same target transmittance within a period of seconds. Manual overrides that had a target transmittance of 62% were excluded from the analysis, since this type of manual override indicates that the user intended to un-tint the window, and thus was seeking to decrease rather than increase shading. On the basis that visual comfort actions occur in response to some perceived visual discomfort, they can be considered an indicator of when occupants experienced visual discomfort.

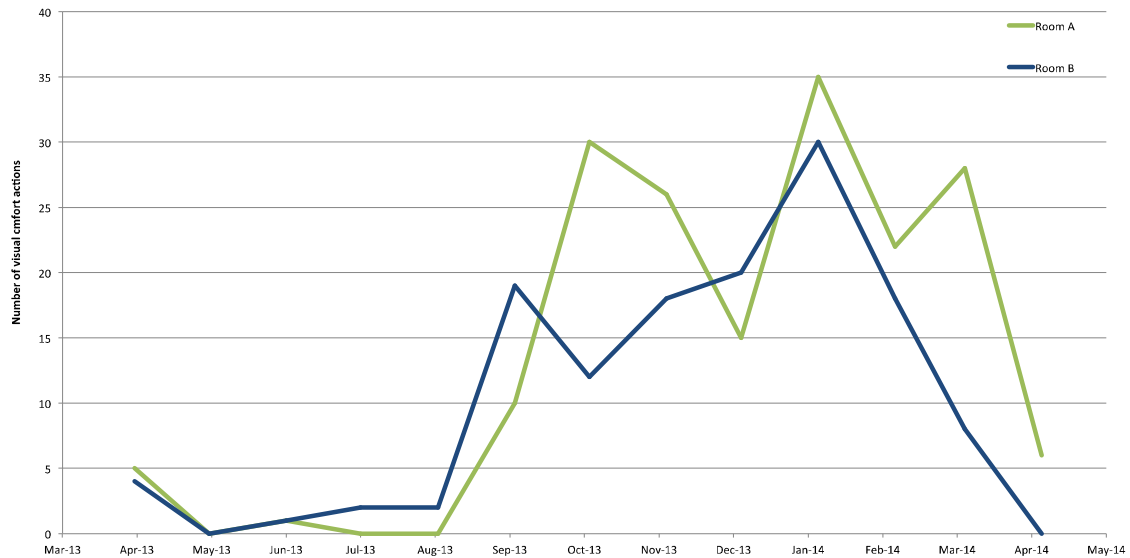
When the data are configured in this way, it is possible to plot them using the same axes. Figure 8.22 shows how the monthly totals for manual overrides in room A, manual overrides in room B, and blinds in room B vary over the data collection period.



**Figure 8.22 Visual comfort actions (monthly totals) over time in each room**

It can be seen that, in September 2013, there is a sharp increase in room A manual override actions and a moderate increase in room B blind usage. These increased levels are sustained for the duration of the winter months. This echoes the previous results that showed a strong relationship between solar altitude and blinds/manual override usage. The difference between the two rooms is also clear to see, in terms of the nature of visual comfort actions in the each room, *i.e.* significantly more manual override actions in room A than in room B.

To allow a more direct comparison between the two rooms, it is useful to look at the undifferentiated visual comfort actions, *i.e.* with blinds and manual override actions in room B combined. Figure 8.23 shows the monthly totals of visual comfort actions over the data collection period in each room.



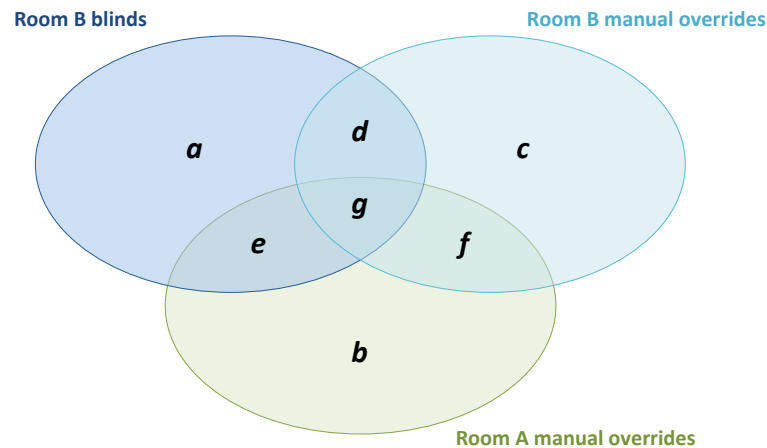
**Figure 8.23 Combined visual comfort actions (monthly totals) over time in each room**

There are generally more visual comfort actions in room A than in room B. The total over the data collection period for room A is 178 and for room B is 134. This equates to approximately 25% more visual comfort actions in room A. A possible explanation for this lies in the way blind usage was recorded. Occupants did not retract blinds at the end of each day, so it was possible for blinds to be left in a lowered position for several days in a row, without any new entries being made in the blinds diary, whereas the EC windows reverted back to the automated setting after 2 hours. Hence, the higher number of visual comfort actions observed in room A does not directly indicate that the occupants in this room experienced more episodes of visual discomfort. This might also explain the noticeable difference in visual comfort actions in each room in October and November 2013, with a greater number in room A in both cases. It can also be seen that, in both rooms, there is a sharp increase in autumn, when solar altitude starts to decrease, which is consistent with previous results.

### 8.5.2 Cross-sectional study of visual comfort behaviour

By looking at the visual comfort actions of occupants in each of the two rooms around the same time (*i.e.* cross-sectional), further insight can be gained into the ways in which the occupants in each room responded to the same external lighting conditions. The body of observed visual comfort behaviour data can be considered as being made up of three data sets: manual overrides in room A, manual overrides in room B and blind usage in room B. The data sets overlap chronologically when visual comfort actions are employed in both rooms at around the same time, in response to the same external conditions (*i.e.* sun position and façade illuminance). Thus, the cross-sectional analysis provides insights into how occupants in each room chose to address visual discomfort, particularly when they responded differently to the same external conditions.

If the three data sets are represented in the form of a Venn diagram (Figure 8.24), each intersection represents a different permutation of visual comfort action from occupants in both rooms at a given point in time. Each set was assigned a category to facilitate the analysis, as indicated by the letters *a* - *g* in the diagram.



**Figure 8.24** Three overlapping data sets, representing observed visual comfort behaviour in the two rooms. The letters *a* - *g* indicate the seven categories used in the analysis.

For two or more actions to be considered as having been made in response to the same external conditions, they need to have occurred within a specific short time period, *i.e.* in which external conditions were largely stable. After some investigation of different time periods, a period of 10 minutes was selected, because it was considered small enough to capture visual comfort actions that were made in response to broadly the same external conditions. A smaller time frame was not considered because the analysis could then be undermined by any inaccuracies in the times recorded in the blinds diary, which could be a matter of several minutes. A larger time frame was ruled out because it might include visual comfort actions made in response to a different set of conditions.

Table 8.2 summarises the seven visual comfort behaviour categories and the number of cases that were found in each category. The shaded rows indicate the categories that contain the three largest proportions of cases.

**Table 8.2 Visual comfort behaviour categories. The highlighted rows indicate the three categories that represent most cases (over 90% in total).**

Category	Description	Number of cases
<i>a</i>	Occupants in room B used the blinds but EC window manual control was not used in either room around that time.	92 (44%)
<i>b</i>	Occupants in room A used EC window manual control, but neither EC window manual control nor blinds were used in room B around that time.	75 (36%)
<i>c</i>	Occupants in room B used EC window manual control and did not use blinds, and occupants in room A did not use EC window manual controls around that time.	4 (2%)
<i>d</i>	Occupants in room B used both EC window manual control and blinds at around the same time.	3 (1%)
<i>e</i>	Occupants in room A used EC window manual control and occupants in room B used the blinds at around the same time.	28 (14%)
<i>f</i>	Occupants in room A and B used EC window manual control at around the same time.	1 (0.5%)
<i>g</i>	Occupants in room A used EC window manual control and, at around the same time, blinds and EC manual control were used in room B.	4 (2%)

It can be seen that the vast majority of cases fall into three of the categories: *a*, *b* and *e*, and that these three categories represent more than 90% of the observed visual comfort behaviour. In the following sections, the results for each category are discussed in more detail, starting with the categories containing the greatest number of cases.

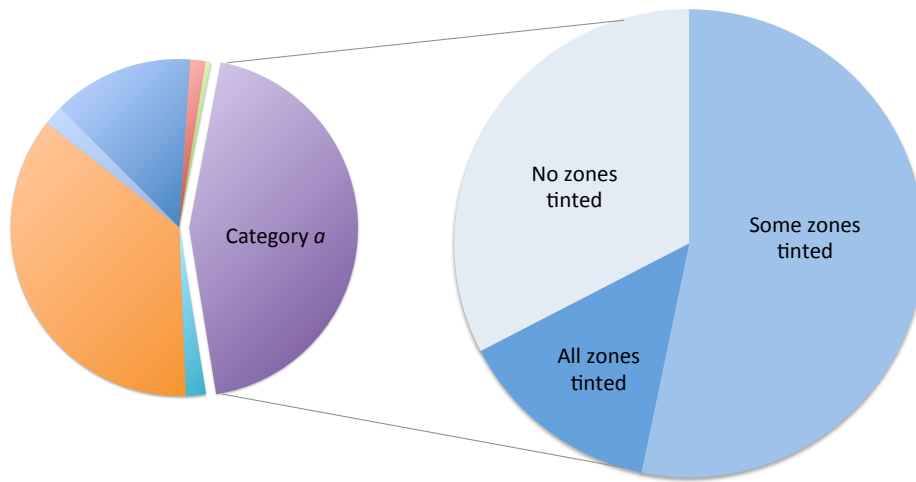
#### **Category *a* (44%): Blinds used in room B, no observed action in room A**

In this category, the occupants of room B lowered the blinds only (*i.e.* did not manually tint the windows first). This behaviour was also described by the interview data (Chapter 7), in which participants from room B indicated that when visual discomfort arose, they usually lowered the blinds without attempting to manually tint the windows first. On this basis, the behaviour exhibited in these cases might suggest that (a) occupants perceived there to be a need for more shading and (b) they believed that adequate shading could only be provided by lowering the blinds.

Around the same time, no visual comfort action was observed in room A. The interview data (Chapter 7) indicated that participants from this room felt generally satisfied with the EC windows. Thus, the behaviour (in this case, non-action) of room A occupants in these cases might suggest that they were satisfied with the level of visual comfort provided by the EC windows in automatic mode. (However, this assumes that the absence of a manual override in room A signified satisfaction with conditions, and that the occupants did not lower the blinds on these occasions. In the absence of detailed blind use data for room A, this assumption is held based on what is known about the general blind usage pattern in room A.)

Category *a* can be further sub-divided based on EC window state, in order to gain further insight into conditions at these times (Figure 8.25). There are three sub-categories: (i) No zones tinted, (ii) some zones tinted and (iii) all zones tinted.





**Figure 8.25 Sub-divisions of Category *a* based on window state**

It can be seen that in the majority of category *a* cases, either no zones were tinted or some zones were tinted, with a small proportion having all zones tinted. In cases when no glazing was tinted or some glazing was tinted, the use of the blinds might suggest that occupants chose to increase shading by lowering a blind, even though there was capacity to increase the level of shading provided by the EC window by manually tinting the glazing. Again, this echoes the findings of the interviews, which suggested that room B participants often ignored the EC manual controls in favour of the blinds when they experienced visual discomfort. When all the glazing was tinted, the use of the blinds is more straightforward, as it might indicate that occupants found the shading provided by the EC windows insufficient, and given that further tinting of the glazing was not possible, lowered the blinds.

**Category *b* (36%): EC window manually tinted in room A, no observed action in room B**

In this category, occupants in room A manually tinted the EC window, suggesting that occupants required shading, and that they found the level of shading provided by the EC window in automatic mode to be insufficient. Around the same time, there was no observed action in room B, suggesting that they were satisfied with conditions in their room at that time.

It is surprising that there should be so many occasions when the same external conditions resulted in apparent visual discomfort in room A and not in room B. However, this is likely to be due to the fact that the blinds diary could only record new instances of blind use; if the blinds were already in a lowered position from a previous day, then no blind use was recorded. By examining the HDR images from room B, it was found that in 42 of the 75 cases, the blinds were already lowered from a previous day. If these cases were discounted, only 20% of cases would fall into Category *b* and the discounted cases would become Category *e* cases.

**Category *e* (14%): EC window manually tinted in room A and blinds lowered in room B**

In this category, occupants in both rooms carried out visual comfort actions of different types (manual tinting of EC windows in room A and the lowering of blinds in room B). The behaviour exhibited in these cases resonates with previous findings, *i.e.* that the occupants of each room tended to respond differently to visual discomfort, with those in room A more likely to use manual EC controls and those in room B more likely to use the blinds. As such, this is considered to be “typical” behaviour, so it is surprising that there are not more cases in this category. However, it is possible that the number of Category *e* cases may have been underestimated, in two ways:

*(i) Manual overrides within 2 hours*

The proportion of Category *e* cases rises to 21% if manual overrides up to two hours prior to the lowering of blinds are included. These additional cases are worth considering because of the fact that a manual command is held for a period of two hours, after which the system reverts to automatic mode. Thus, in these cases it is not known whether an occupant in room A would have manually tinted the window closer to the time when the blinds were lowered, had the window not already been tinted by an earlier manual override.

(ii) *Blind use not captured by blinds diary*

As mentioned previously, it is possible that there are a number of additional Category *e* cases that were not accounted for due to the fact that the blinds diary did not include cases where blinds were already in a lowered position from a previous day. 42 cases were found in Category *b* in which the blinds were already lowered from a previous day. If these 42 cases were added, Category *e* cases would increase to 35%. However, this is speculative, because in these cases it is not possible to establish the time at which the blinds would have been lowered, had they not already been in a lowered position from a previous day.

**Category *d* (1%): EC window manually tinted and blinds lowered in room B, no observed action in room A**

These are cases in which occupants in room B attempted both EC window manual control and blinds, presumably in order to resolve visual discomfort. The low proportion of cases in this category indicates a lack of engagement of users in room B with the EC window manual controls. They rarely tried to use the EC window manual controls to address their needs; in most cases going straight to the blinds. This echoes the interview findings, in which room B participants reported that they tended to use the blinds to resolve visual discomfort without trying the window controls first.

**Category *f* (0.5%): EC manual controls used in both rooms**

In these cases, occupants in both rooms appeared to respond to the same conditions in the same way, by using the EC manual controls. However, only one case was found in this category, illustrating the rarity of such an event. The very small proportion of cases that fall within this category suggests that the occupants of the two rooms hardly ever responded in the same way to the same external conditions.

**Category *c* (2%): EC window manually tinted in room B, no observed action in room A**

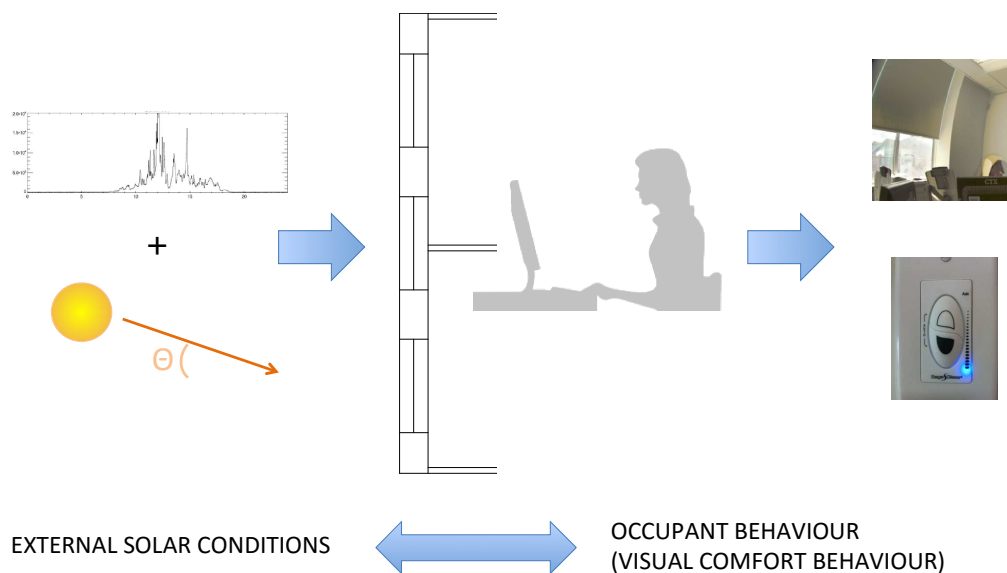
These are cases in which the occupants in room B manually tinted the EC window, which suggests that (a) they were experiencing visual discomfort and (b) they chose to address this by manually tinting the window and not by using the blinds. The low number of cases found in this category illustrates the fact that this behaviour is not typical. In fact, it is surprising that there are any cases in this category at all. It is possible that some (or all) of these cases exist as a result of ambiguous circumstances, *e.g.* the blinds on one window were already lowered from a previous day and a zone in the other window was manually tinted.

**Category *g* (2%): EC windows manually tinted in both rooms and blinds lowered in room B**

These are the cases when occupants in both rooms apparently experienced visual discomfort and chose to address it by manually tinting the EC window and, in the case of room B, by also lowering the blinds. In other words, all three behaviours were observed around the same time. These cases are rare, as indicated by the low number of instances.

## 8.6 Daily visual comfort actions and solar conditions

In the previous section, it was seen how the number of visual comfort actions varied seasonally over the 12-month data collection period, with a higher number of visual comfort actions at times of the year when low solar altitude is more prevalent (*i.e.* in winter). This section examines the relationship between daily visual comfort actions and solar conditions on a given day, which can be characterised based on the pattern of solar irradiance over the course of the day and the solar altitude when the sun is shining onto the facade. The relationship is illustrated in Figure 8.26.



**Figure 8.26 Relationship between daily exterior conditions and visual comfort behaviour**

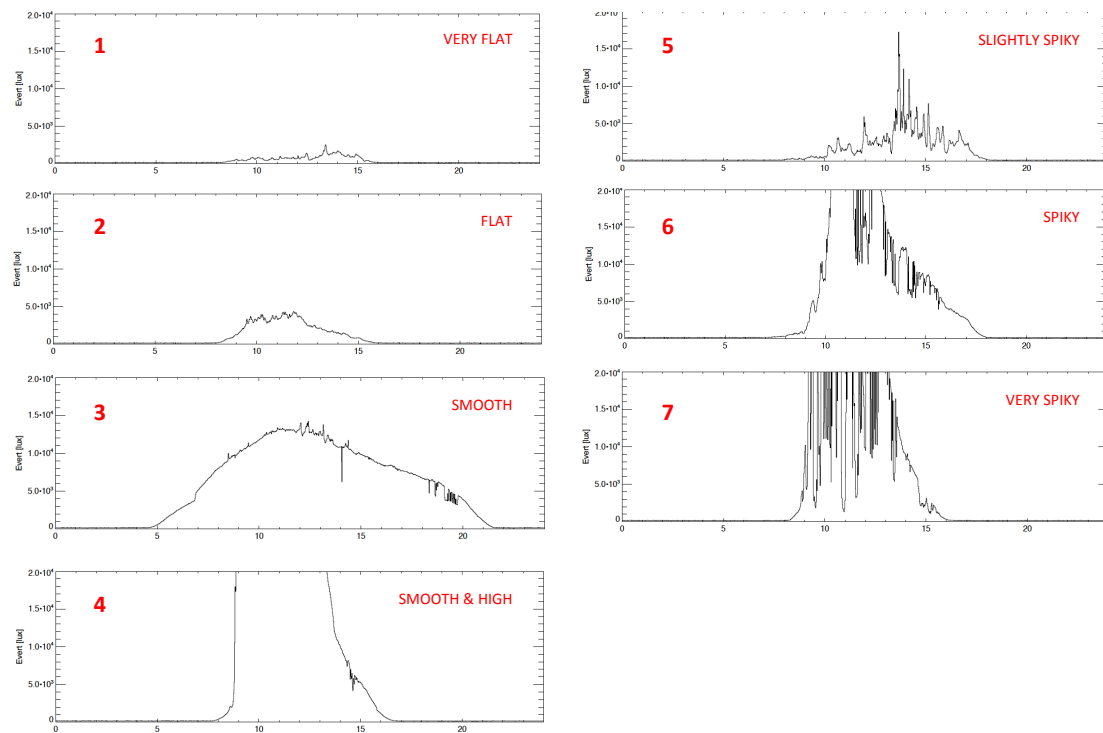
The total number of visual comfort actions for each day was simply obtained by adding the number of manual override clusters or blind-pulls together. If no manual overrides or blind-pulls occurred, this number was zero.

### *Sensor profile classification*

As explained previously, the intensity of sun on the façade, as measured by the exterior façade sensor, was logged by the EC control system. This enabled the

values for any one-day period (24 hours) to be plotted, resulting in a sensor profile for each day. It was observed that the profiles appeared to be broadly distinct in character. For example, some days had a profile that was relatively smooth, whereas others had a profile that included several peaks or spikes of several orders of magnitude. It was considered that the “spikier” types of profile represented more challenging conditions in terms of the visual comfort of occupants, as shown in section 8.2.2 and 8.4.2.

The exterior sensor profile for each day in the data collection was examined by eye. Weekends and bank holidays were not included (because if the rooms were unoccupied, then an absence of visual comfort action could not be linked to exterior conditions). This resulted in a total of 267 days to be analysed. Each profile was classified using seven categories in increasing levels of “spikiness”, as shown in Figure 8.27.



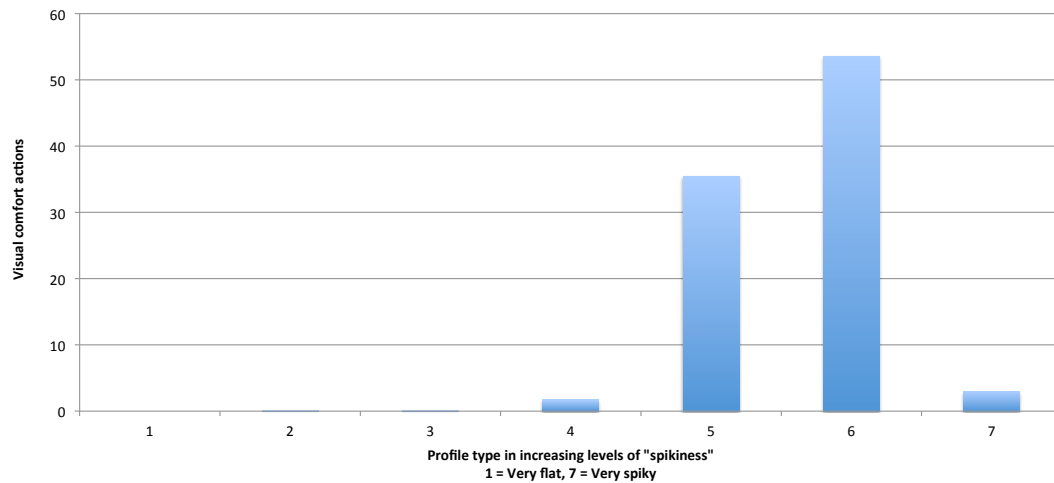
**Figure 8.27** Exterior sensor profile classification

### *“Daily” sun position*

The sensor profile alone does not tell the full story; it must be coupled with sun position in order to evaluate the potential for visual discomfort, *i.e.* a spiky sensor profile with predominantly low solar altitude is more challenging than a spiky sensor profile with high solar altitude. To characterise sun position in daily terms, the solar altitude when the sun was perpendicular to the façade was taken as the “daily solar altitude”. For these rooms, this equates to solar altitude at an azimuth of 147°.

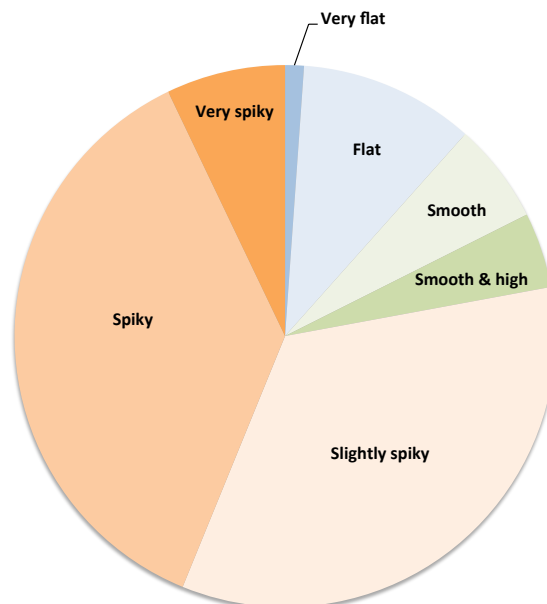
### *Visual comfort actions and sensor profile type*

Figure 8.28 shows the number of visual comfort actions against the sensor profile type, in increasing levels of spikiness. The graph suggests that there is a relationship between the number of visual comfort actions and the exterior sensor profile type; namely that visual comfort actions increase with increasing spikiness of profile. It can be seen that the number of visual comfort actions decreases when the profile spikiness is categorised as “very spiky” (category 7). This could be because profiles with a “very spiky” profile have numerous peaks very close together, which may in fact be less challenging for the EC window control system than numerous isolated spikes (or “lone spikes”). This indicates that a “very spiky” profile poses the same level of challenge to the EC control system as a “smooth” profile of the same magnitude (*i.e.* as if the peaks were joined up).



**Figure 8.28** Visual comfort actions and exterior sensor profile type (corrected for number of days in the data collection period with each profile type)

Looking at the data collection period as a whole, it can be seen that the vast majority of days had exterior sensor profiles that fell into one of the spiky categories, *i.e.* slightly spiky, spiky or very spiky (Figure 8.29). Hence, the data in Figure 8.28 were corrected for the number of days with each profile type.

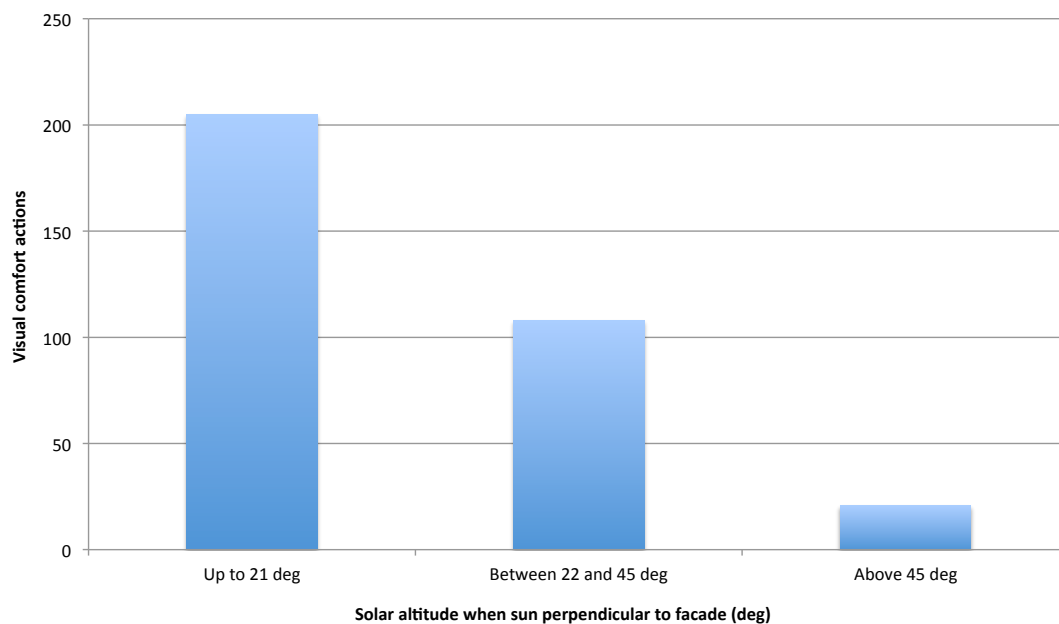


**Figure 8.29** Number of days with each exterior sensor profile type in the data collection period



### *Visual comfort action and sun position*

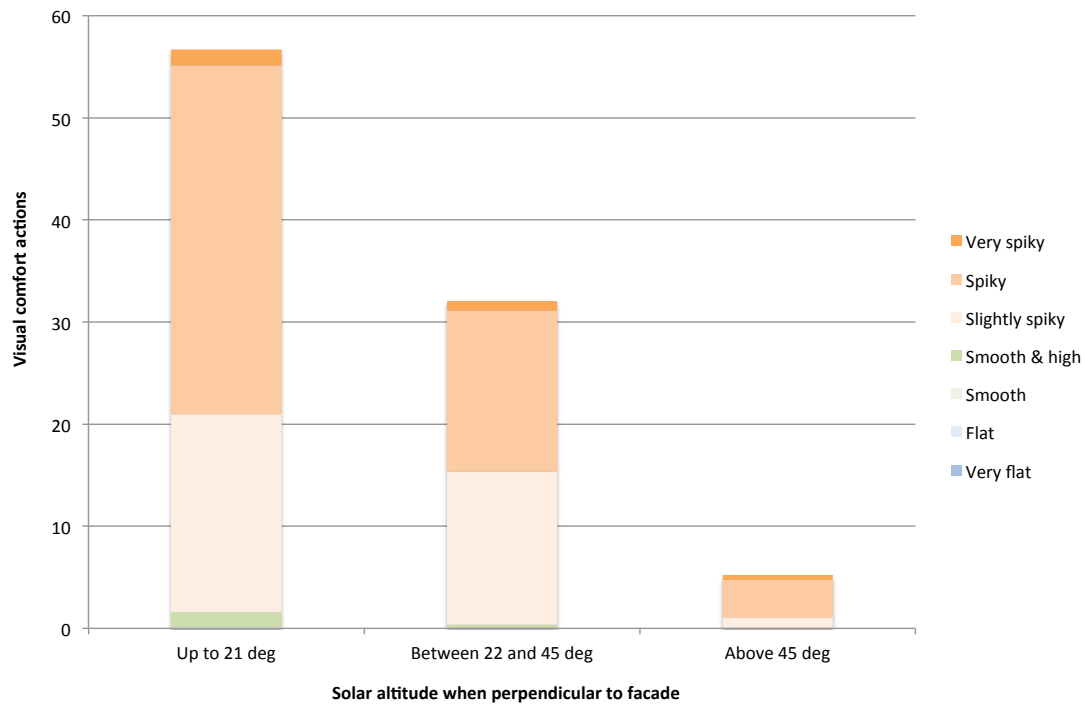
Figure 8.30 shows the number of visual comfort actions that occurred under three different categories of solar altitude: Low (up to 21°), Medium (22° – 45°), and High (above 45°). These ranges of solar altitude were chosen because they occurred on an equal number of days in the data collection period. The graph indicates that more visual comfort actions occurred at lower solar altitudes.



**Figure 8.30** Visual comfort actions at different solar altitudes

### *Visual comfort action, profile type and sun position*

The data appear to show a relationship between the number of visual actions and sun position and the number of visual comfort actions and exterior sensor profile spikiness. Given that the sun position and profile spikiness can be considered together to represent the daily solar conditions, by combining them it should be possible to show a relationship between the number or visual comfort actions and the solar conditions on a given day. In Figure 8.31, the three variables are plotted together. The data have been corrected for number of days with each profile type, as previously noted.



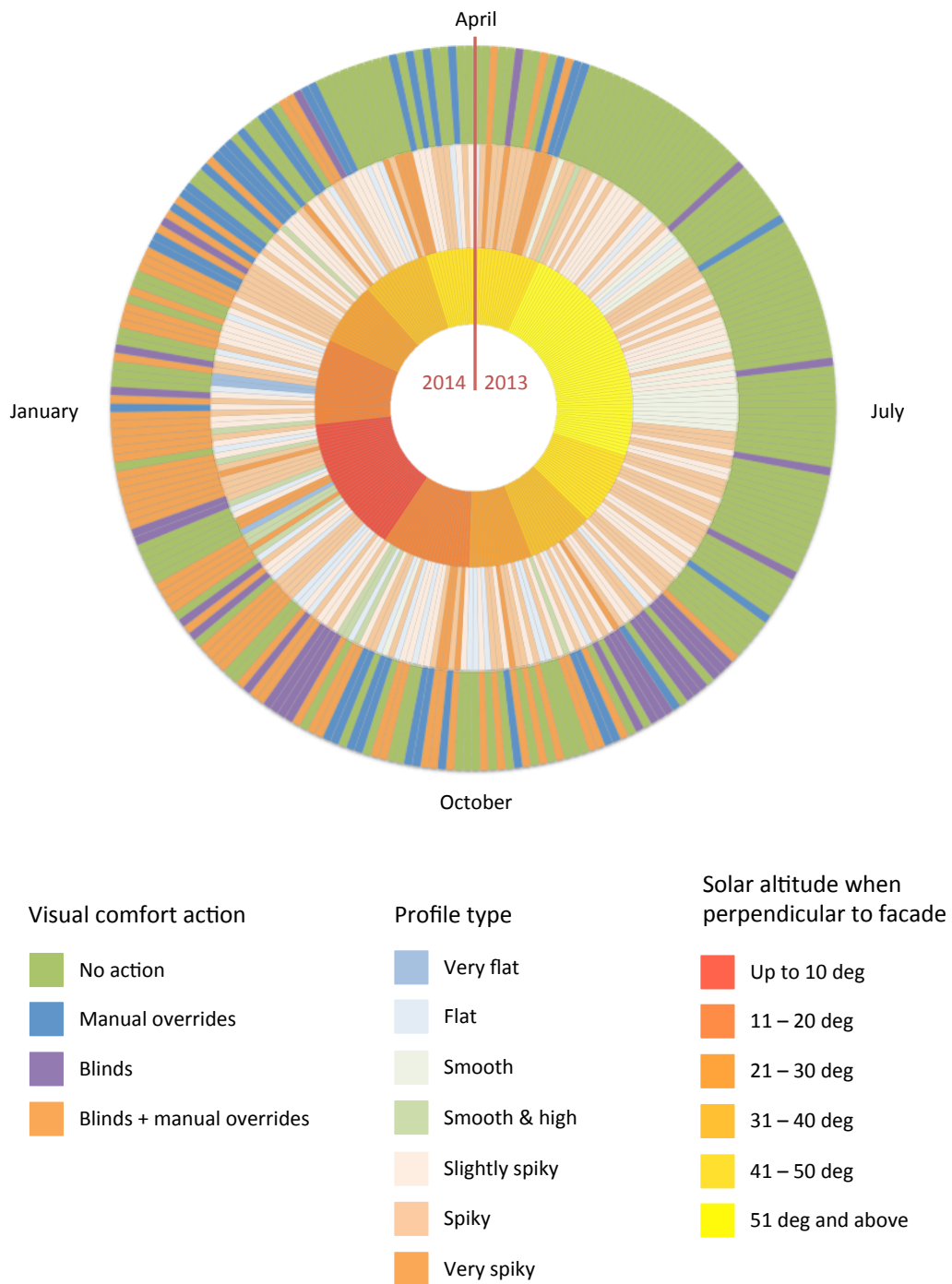
**Figure 8.31 Visual comfort actions under different solar conditions (corrected for number of days with each profile type)**

Figure 8.31 indicates a strong relationship between solar altitude and the number of visual comfort actions, as previously seen. The addition of the profile type variable shows that the “Spiky” profile type is dominant within each cohort of solar altitude, even after the data has been corrected for profile type. This suggests that there is a relationship between the profile type, solar altitude (perpendicular to the façade) and number of visual comfort actions.

#### *Daily visual comfort action and solar conditions over 12 months*

Figure 8.32 is a graphical illustration of visual comfort actions and solar conditions over the entire data collection period (excluding bank holidays and weekends). The outer ring represents the nature of visual comfort action that occurred on a given day; this could be blinds only, EC manual controls only, blinds and EC manual controls, or no action. The middle ring shows the external sensor profile type on each day, and the inner ring represents the solar altitude when the sun was perpendicular to the façade on each day. The graph clearly

shows the relationship between visual comfort action and the solar altitude, with many “no action” days occurring in the April-July quadrant. The relationship between profile type and visual comfort action is less obvious, although it can be seen that there are more “Smooth” type profiles during the summer.



**Figure 8.32 “Clock graph” showing daily visual comfort actions, profile type and solar altitude over the 12-month data collection period**

The outer ring represents the type of visual comfort action that occurred, the middle ring shows the external sensor profile type, and the inner ring represents the solar altitude when the sun was perpendicular to the façade.

## 8.7 Discussion

It can be seen from the observed visual comfort behaviour data and subsequent analysis that the occupants of the two rooms typically responded differently to visual discomfort. In room A, they regularly used the EC window controls to manually tint the windows, and in room B they usually lowered the blinds without using the EC window controls. This echoes the findings of the interview data, described in Chapter 7. The analysis of combined visual comfort behaviour suggested that the occupants of the two rooms experienced comparable levels of visual discomfort, with both experiencing lower levels during the summer months and an increase in the autumn, when prevailing solar altitude starts to decrease. In fact, the analysis found that occupants of room A were responsible for 25% more visual comfort actions than those of room B. However, the number of visual comfort actions in room B may have been underestimated due to the fact that, if blinds were left down from a previous day, no new blind use was recorded in the blinds diary. The limitations of the methods used to collect data about blind usage are discussed in more detail in Chapter 10.

The analysis of the manual override data showed that most of the manual overrides came from room A, and were aimed at fully tinting the lower half of the large window ( $T = 2\%$ ). It was observed that manual overrides typically occurred in clusters, resulting from repeated pressing of the same button within a short time frame. This behaviour may be suggestive of user impatience with the system, perhaps as a result of the delayed perceptible response of EC windows. Given this finding, it may be useful to enhance the user interface so that further reassurance is given to the user that their input is being processed by the system. Overall, there were relatively few manual overrides that targeted an intermediate level of tint ( $T = 6\%$  or  $20\%$ ), which brings into question the need for the intermediate settings in the manual controls.

The cross-sectional analysis of visual comfort behaviour enabled a more detailed exploration of the times when occupants responded differently to the same external conditions. The category with the largest proportion of cases was found to be the one in which blinds were used in room B but no observed action was taken in room A. This suggests that occupants in room B called for shading in

addition to that provided by the EC windows in automatic mode more frequently than in room A. Furthermore, they chose to address this by lowering a blind rather than manually override the EC control system. This was found to be the case even when the EC windows were not tinted or only partly tinted, *i.e.* when it was still possible to increase shading by manually tinting the windows further. This finding is supported by the interview data, in which room B participants indicated that they preferred to just use the blinds to address visual discomfort, without trying to tint the window manually first.

Looking at the incidence of visual comfort actions over the 12-month data collection period, there was an obvious decrease in activity during the summer months, which indicates that visual comfort actions, and therefore episodes of visual discomfort, are more likely during periods when solar altitude is low. This was further confirmed by examining the number of blind-pulls and manual overrides at different solar altitudes; in both cases, the number of actions was highest when solar altitude was between 11 and 20 degrees. It was also seen that the number of actions decreased when solar altitude was below 10 degrees; at these altitudes, the sun would have been hidden behind neighbouring buildings.

The internal lighting conditions in room B around the times when blinds were lowered were studied, using HDR-derived luminance metrics. It was expected that the luminance metrics taken from images before and after blinds were lowered would display a clear transformation, commensurate with a visual discomfort condition before and a (more) visually comfortable condition afterwards. Though the luminance metrics did change before and after the blinds were lowered, the differences were not consistent or clear enough to enable any of the metrics to be linked to the visual comfort behaviour of occupants. Although this is probably due to a number of factors, the main reason is likely to be that the blinds were often not fully lowered, meaning that patches of bright sky, visible sun and/or sunlight patches may have been still visible in the HDR image taken after blinds were lowered. Given the differences between the field of view of occupants and that of the cameras, an analysis such as this might produce more firm results using cameras located more closely to the occupants' eye position. Due to the low numbers of manual overrides in room B, and the

lack of HDR data from room A (where most of the manual overrides occurred), it was not possible to study the relationship between luminance metrics and visual comfort behaviour in room A. Had it been possible to study room A, perhaps more obvious changes in the luminance metrics would have been evident, since there would have been more data points involved. The advantages and disadvantages of the HDR method used in this study are discussed further in Chapter 10.

The EC window state in room B at the times when blinds were lowered was analysed, and the results indicated that in almost half of the times studied, the glazing was un-tinted. When the window state 10 minutes later was examined, it showed that in almost half of cases, the average window transmittance had decreased. This suggests that if occupants in room B had not lowered the blinds, in about half the cases, the glazing would have been tinted by the automatic control system. However, in a significant number of cases (39%), the average window transmittance had remained the same after 10 minutes, and in the remaining 14% of cases it had actually increased. A study of façade illuminance in these “no change in %T” and “increase in %T” cases revealed that many could be linked to continuous fluctuation in façade illuminance, such as that caused by fast-moving broken cloud. In the other cases, the façade illuminance was stable but high; indicating that occupants found the level of shading provided by the windows inadequate and thus lowered the blinds. In a similar way, the façade illuminance sensor profiles were studied around the times when manual overrides occurred. This analysis indicated that almost half of the manual overrides studied could be linked to fluctuating façade illuminance.

This aspect was further illustrated by an analysis of the daily exterior daylight conditions and visual comfort actions. The exterior sensor profile of each (occupied) day in the data collection was categorised into one of seven profile types, with Type 1 having the least number of spikes in the profile (*i.e.* a flat or smooth curve) and Type 7 having profiles with many spikes. This enabled the daily total of visual comfort actions to be plotted against profile type, which indicated that there is a proportional relationship between the number of visual comfort actions per day and the spikiness of the exterior sensor profile.

However, the relationship did not appear to be linear; there were fewer visual comfort actions for “Very spiky” than for “Spiky” profile types. This indicated that days with façade illuminance spikes very close together elicit the same visual comfort action response as days with “Smooth & high” profiles, *i.e.* as if the spikes were joined up. The solar altitude when the sun was perpendicular to the façade was taken as a “daily” sun position. This enabled the relationship between daily visual comfort actions and sun position to be explored, and showed that a strong relationship exists, with greater numbers of visual comfort actions occurring at lower solar altitudes (below 21°).

It could be useful to go further and attempt to combine the sensor profile spikiness and sun position into a single number or index, representing solar conditions on a given day. With detailed weather forecasting, it would then be possible to calculate an index such as in advance, to predict the degree to which the EC control system would be challenged. In this way, the control system could be configured to anticipate challenging conditions before they arise. In this analysis, the “spikiness” of each profile was obtained by eye, and thus is not a robust enough measure to allow it to be incorporated into a numerical index. In future, it might be valuable to use a more robust mathematical method to quantify the spikiness of sensor profiles, *e.g.* by calculating the number and frequency of peaks in a profile. Such a method could be automated and applied to large numbers of profiles, and then combined with sun position as described. This approach was considered here, based on methods such as those used by Harrouni *et. al.* [2005] to determine the potential of solar energy systems, but due the level of complexity involved, it was decided that for the purposes of this study, the method used was sufficient.

A graphical view of the full 12 months’ data was presented, showing the nature of visual comfort actions that occurred on each day, together with the sun position and profile type. This demonstrated the relationship between sun position and visual comfort action, *i.e.* that there were more days with no visual comfort action during periods when the solar altitude was high. The relationship between profile type and visual comfort action was less clear, since a mix of



profile types occurred throughout the 12-month period in a less discernible pattern.

## **8.8 Summary**

In this chapter the observed data were described, revealing how occupants addressed visual discomfort over a 12-month period. The data, and subsequent cross-sectional analysis, indicate that the occupants of the two rooms responded differently to perceived visual discomfort, with regular use of the EC window controls in room A and frequent use of the blinds in room B. This resonates with the findings of the interview data, described in Chapter 7, in which participants from room B espoused a preference for using the blinds to provide shading. By examining visual comfort actions over the 12-month data collection period, it was seen that the number of actions appeared to increase as solar altitude decreased, and this was confirmed by further analyses of visual comfort actions and solar altitude. Thus, the observed data indicate that visual discomfort was more likely to occur at times of low solar altitude.

A detailed analysis of the manual override data was carried out, further illustrating the stark differences in usage patterns in the two rooms. The clustered nature of the data indicates that users might benefit from additional reassurance from the system that their request has been registered even though there may be no visible change in the glazing. This could help to overcome the disadvantage of non-instantaneous response of the glazing. The results also indicate that the intermediate tint settings were rarely used in either room. Thus, an interface that allows users to fully tint or un-tint the glazing, perhaps with one intermediate setting, might suffice.

A study of the EC window state in room B around the times when blinds were lowered was undertaken. The results indicate that, whilst in many cases, tinting was increased automatically after ten minutes, in a significant number of cases the tint level either remained static or increased. By examining the façade illuminance profiles on these occasions, it was found that in many cases, spikes in the façade illuminance had occurred, which may have been severe enough to

cause visual discomfort for occupants, but not prolonged enough to trigger a response in the EC window control system. A similar analysis was conducted for manual overrides, whereby the façade illuminance profile around times of manual override were examined. This also found that in many cases manual overrides occurred during times of fluctuation in façade illuminance. In the final section, this relationship was examined on a diurnal basis, which revealed strong evidence for a relationship between the number of visual comfort actions and the prevalent solar conditions (position and level of fluctuation) in a given day.

The results of these analyses suggest that fluctuating façade illuminance represents a particular challenge to the EC window control system, since it is possible for a spike in façade illuminance to cause acute discomfort for an occupant, but if the increase in façade illuminance is not sustained, it will not necessarily trigger the automatic control system to tint the glazing. In these cases, occupants must act to resolve the discomfort, either by manually tinting the glazing or by lowering a blind.

## **Chapter 9**

### **The effect of EC glazing tint colour**

The blue colour of the EC glazing when tinted is one of the most striking features of the technology. However, it is not only an aesthetic consideration; the colour of the glazing in its tinted state affects the spectral content of light entering through it, and thus the colour appearance of objects within the room and the appearance of objects viewed through the window. As discussed in the literature reviews in the early chapters, it is also possible that the colour of the glazing affects occupants in other, non-visual ways, such as their level of alertness or tiredness.

These issues were explored as part of the self-reported data collection, by the inclusion of questions about the effect of the glazing tint on view through the window, colour appearance and various non-visual parameters (emotional state, alertness and perceived pleasantness of the space). This chapter focuses on the results of these aspects of the data collection. In addition, two further pieces of work that investigated the impact of the glazing tint colour are described.

In the interviews, participants were asked for their views on how the EC glazing (when tinted) affected the view through the window and the appearance of colours in the room. In the questionnaires, participants were asked to rate the following using a scaled response:

- Self-reported alertness/tiredness (Q12)
- Self-reported emotional state (Q13)
- Clarity of the view through the window (Q14)
- Ease with which they could tell the local weather condition by looking through the window (Q15)
- Pleasantness of the space (Q18)
- Appearance of colours in the room in terms of how natural (Q19.1) and vibrant (Q19.2) they looked

Since the above questionnaire items were asked with respect to how participants felt at that moment, the responses can be linked to the average EC glazing transmittance at the time of questionnaire response.

## **9.1 View out**

### **9.1.1 Interview data**

In the interviews, participants were asked how they felt the tinting of the EC window affected their ability to clearly see out, for example to judge local weather conditions:

*When the windows are tinted, how does it affect your ability to see through the windows?*

As explained in Chapter 7, participants' responses reflected a range of positive, negative and neutral perspectives about the view through the EC windows. On the positive side, participants indicated that they were enjoying being able to see out. Particularly during the first interviews following the window retrofit, several participants reported that the new windows were an improvement upon their previous windows, which had been in poor condition, because they could now see out more clearly.

One of the significant advantages of EC glazing as a daylight control device is that it allows a continuous view out, even when fully tinted. A few comments indicated the perceived benefit of having a view out even when the windows were tinted; however, there were relatively few comments in this vein. This is likely to be a result of continued use of the blinds in room B (from whence most of the interview data came), which meant that this advantage was limited.

On the negative side, there was a consensus among all participants that the tinting distorted the view of the sky, making it more difficult to judge local weather conditions and the time of day. Several suggested that the tinting made the sky look darker, and hence any cloud present was perceived as being more likely to bring rain than perhaps it was in reality. Also, since the control algorithm was such that the upper panes were more likely to be tinted, this phenomenon particularly affected views of the upper sky, especially when

viewed from a seated position in the room. Another recurring comment was that it was difficult to tell if it was raining, however, this may have been the case even with traditional windows, since prevailing weather conditions meant that rain rarely fell against the façade.

Several comments were made about dirt on the windows, inside and out, that made it difficult to see out clearly. In most cases, these comments came from participant B2, but the issue was also mentioned by participant B3. The context of these comments is important, as it was suggested by participant B2 that the EC windows were in some way particularly prone to becoming dirty or showing dirt. It is quite likely that they were no more prone to dirt build-up than a traditional window, but because the previous windows were badly fogged, it would not have been obvious to occupants that they had not been cleaned. These comments reflect disquiet about the technology and were included within the theme “Doubts and misconceptions about EC windows”, as described in Chapter 7.

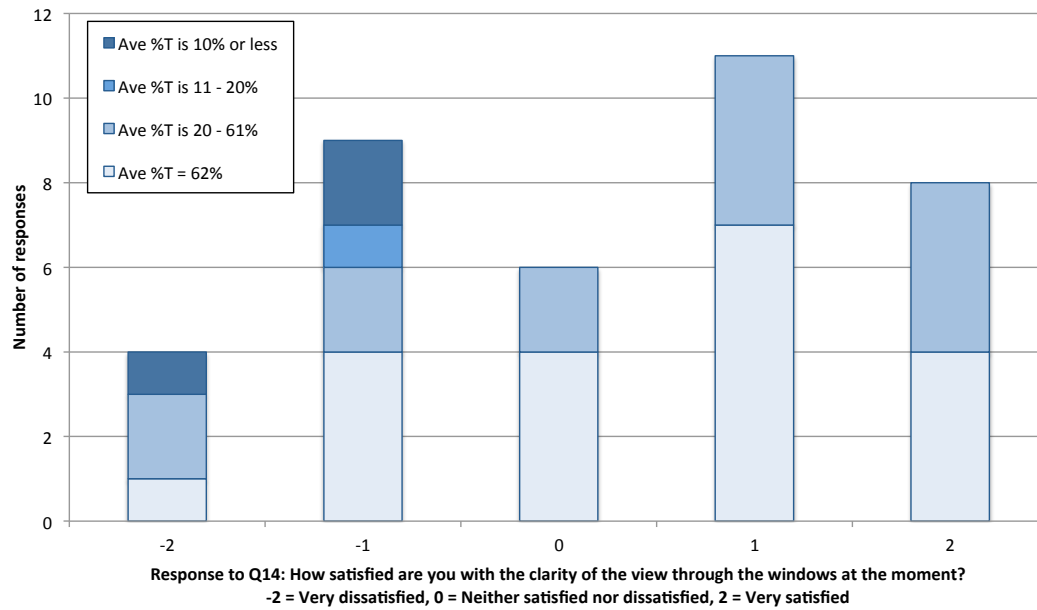
### **9.1.2 Questionnaire data**

As part of the questionnaire, participants were asked the following questions:

*Q14: How satisfied are you with the clarity of the view through the windows at the moment?*

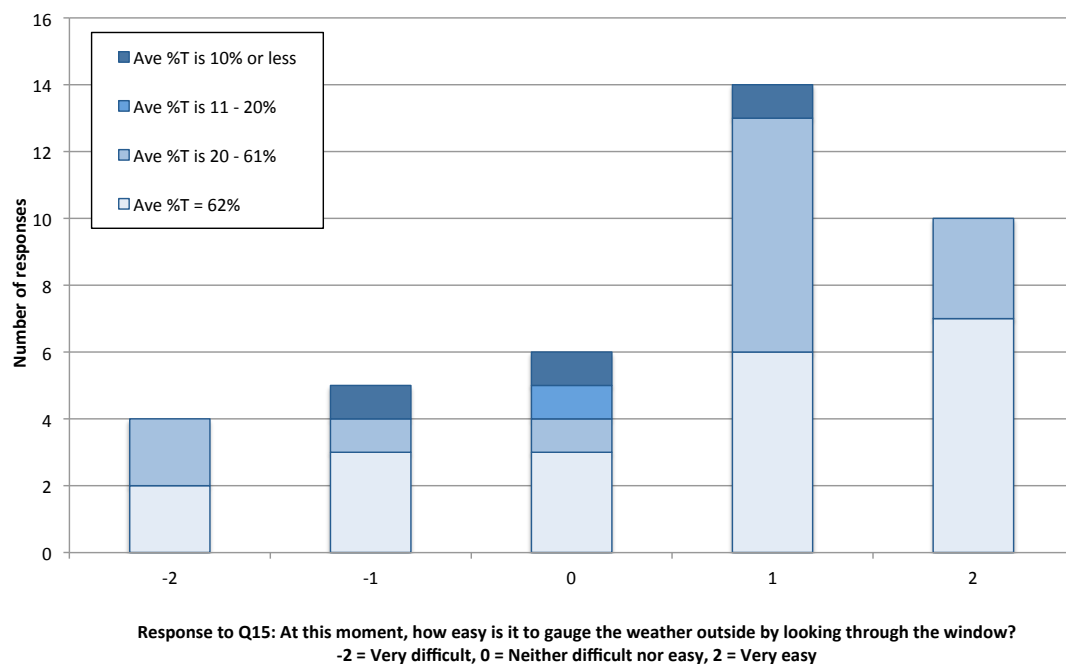
*Q15: At this moment, how easy is it to gauge the weather outside by looking through the window?*

The results, described in Chapter 7, indicated that participants were mostly satisfied with the clarity of the view out and found it easy or very easy to judge the weather. However, there were a considerable number of responses that indicated dissatisfaction with the clarity of the view out, and difficulty with being able to gauge weather conditions, which reflects the findings of the interviews.



**Figure 9.1 Perceived clarity of view through the window and average EC glazing transmittance at time of questionnaire response**

Figure 9.1 shows the perceived clarity of view through the window (response to Q14) with the corresponding area-weighted average transmittance of the EC window at the time of response. It can be seen that a few negative responses (*i.e.* to the left of the neutral point) occurred when the windows had an average transmittance of 20% or less, and that all of the positive responses (*i.e.* to the right of neutral) occurred when the average transmittance was above 20%. This indicates that there may be a relationship between the average transmittance of the EC window and the perceived clarity of the view out. However, the small number of responses, and the fact that most questionnaires were answered when the windows were un-tinted, mean that this result should be viewed with circumspection.



**Figure 9.2 Perceived ease of judging weather conditions and average EC glazing transmittance at time of questionnaire response**

Figure 9.2 shows the perceived ease with which participants felt they could judge the local weather condition (response to Q15) with the corresponding area-weighted average transmittance of the EC window at the time of response. It can be seen that most of the positive responses (to the right of neutral) occurred when the windows were either fully un-tinted or partly tinted (*i.e.* had an average transmittance of between 20% and 61%). There were few negative responses, and these occurred across a range of window transmittances. Thus, the questionnaire data do not reflect the views expressed by participants in the interviews. However, this is likely to be a direct result of the difference in nature of the questionnaire and interview questions; in the questionnaire, questions were asked in relation to a specific moment in time, whilst in the interviews participants were asked for their impressions in more general terms.

## **9.2 The appearance of colours in the room**

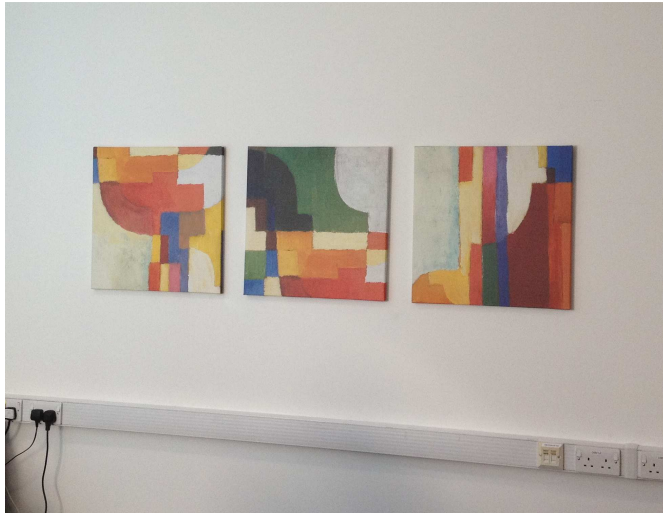
### **9.2.1 Interview data**

In the interviews, participants were asked about how they thought the tinting of the EC windows affected the appearance of colours in the room, including the skin tone of colleagues and the colour of objects:

*When the windows are tinted, do you think it affects the colours in the room in any way?*

Participants' responses to this question were indicative of either a neutral or a negative perspective. The neutral comments suggested that the tinting of the windows had a "strange" effect on the appearance of colours, which was difficult to articulate. Participant B2 in particular reported this effect, and used the word "twilight" to describe it on more than one occasion. On the negative side, two participants from room B felt that tinting had an adverse affect on the appearance of occupants' skin tone, making people appear grey or ill. However, these comments were only made in interviews before March 2013, when the control algorithm was set to consistently keep the lower panes less tinted (even in glare mode). After this point, no such comments were made. Throughout the data collection period, all room B participants indicated that they felt the tinting made colours in the room appear dull, and the room generally appear darker. However, it was also mentioned by two participants in room B that the colour scheme in the room (which was the same as room A) was in itself quite muted, *i.e.* without the effect of the EC glazing tint. One room B participant remarked that when she looked at the artwork on one of the walls (Figure 9.3), she thought it looked unchanged despite the glazing being tinted, and that her ability to distinguish the colours within in was unaffected. This might be an example of colour constancy, whereby the human visual system perceives the colours (hues) of objects, and in particular familiar objects of "known" colour, as constant, despite changes in the colour rendering of the light source, which may change the appearance of colours. It would be interesting to understand more about the role of colour constancy in the perception of colours in the room under different EC glazing conditions; this could be investigated as part of a future study, which will be discussed later.





**Figure 9.3      Artwork in room B**

## **9.2.2              Questionnaire data**

In Q19 of the questionnaire, participants were asked to rate the appearance of colours in their room on a five-point scale in terms of two qualities – naturalness and vibrancy:

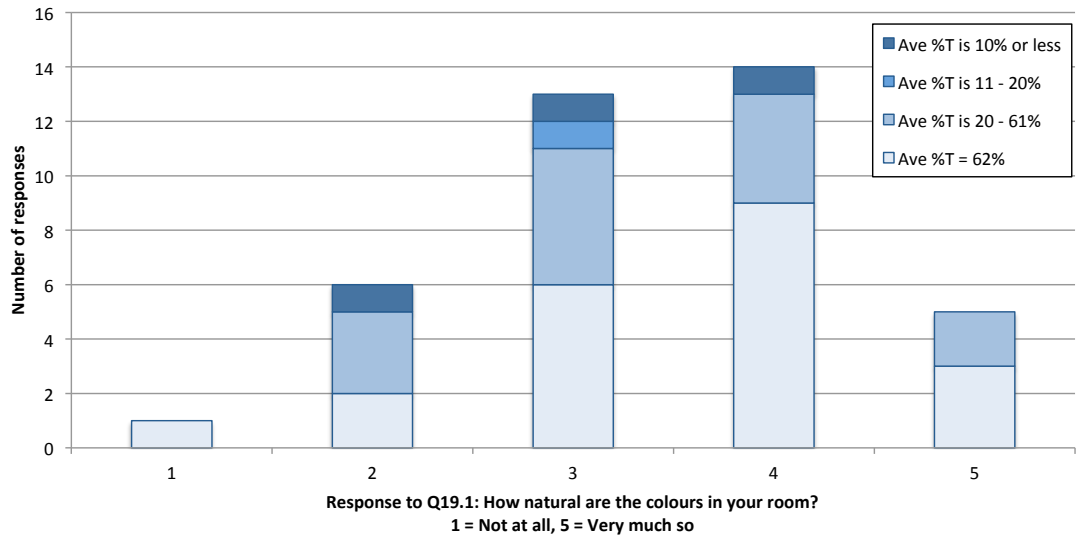
*Q19: Please use the scale below to describe the appearance of colours in your office at the moment.*

*Natural              1 = Not at all, 2 = A little, 3 = Moderately, 4 = Quite, 5 = Very much so*  
*(Q19.1)*

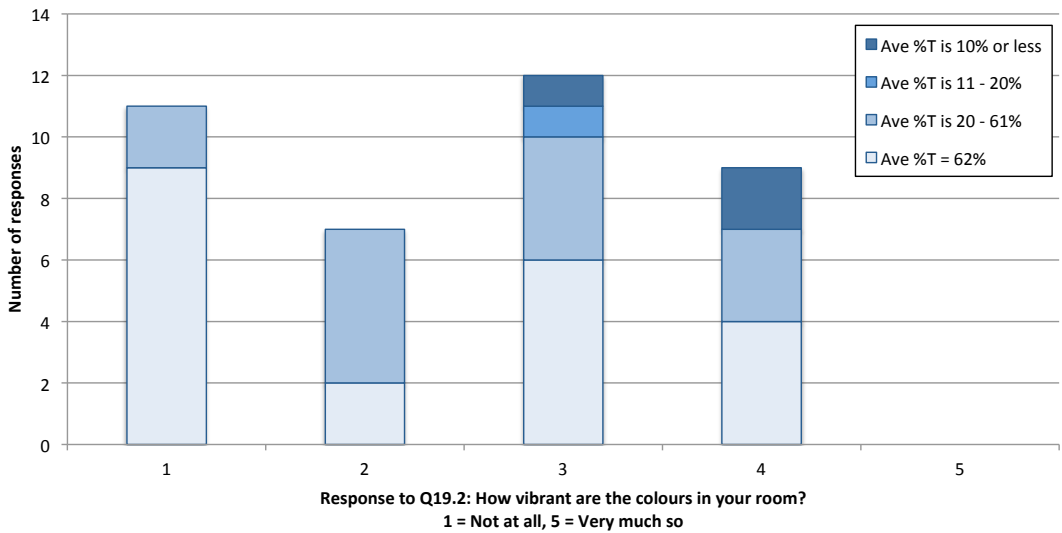
*Vibrant              1 = Not at all, 2 = A little, 3 = Moderately, 4 = Quite, 5 = Very much so*  
*(Q19.2)*

The results were briefly described in Chapter 7, and indicated that most participants felt that colours in their room appeared moderately natural and moderately vibrant. For “Natural”, there were a high number of responses in the “Quite” and “Very much so” categories, and only one in the “Not at all” category”, indicating that participants perceived colours to appear natural at most of the times when they responded to questionnaires. For “Vibrant”, no responses were made in the “Very much so” category and a considerable number were made in the “Not at all” category. This indicates that participants did not consider colours vibrant at the time of questionnaire response. This could be a reflection of the

relatively muted colour scheme employed in the rooms, which was mentioned previously.



**Figure 9.4** Perceived naturalness of colours in room and average EC glazing transmittance at time of response



**Figure 9.5** Perceived vibrancy of colours in room and average EC glazing transmittance at time of response

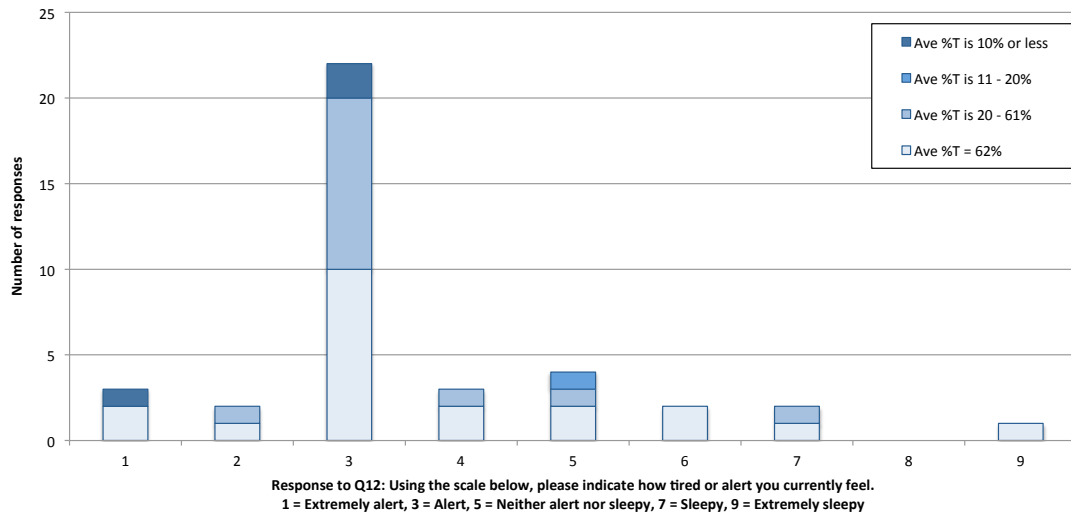
Figure 9.4 and 9.5 show the responses to Q19.1 & Q19.2 with the corresponding area-weighted average transmittance of the EC window at the time of response.

The results shown in Figure 9.4 do not indicate a relationship between the perceived naturalness of colours and the EC window tint. In Figure 9.5, it can be seen that there were no responses in the “Very much so” category and that a small number of responses in the “Moderately” and “Quite” categories occurred when the windows had a low average transmittance. Responses in the “Not at all” and “A little” categories occurred when the windows were either fully un-tinted or partly tinted. This indicates a slight trend towards decreasing window transmittance and increasing perceived vibrancy of colours in the room. However, the low numbers of responses when windows were tinted make it difficult to draw any conclusions from these results about the relationship between perceived vibrancy of colours and EC window tint.

The ability of the questionnaire data to reveal relationships between the perception of participants and the tinting of the EC windows is limited by the fact that the windows were un-tinted at the time of more than half of the questionnaire responses. In order to fully explore these relationships, more questionnaire data would need to be collected at times when the EC windows were tinted.

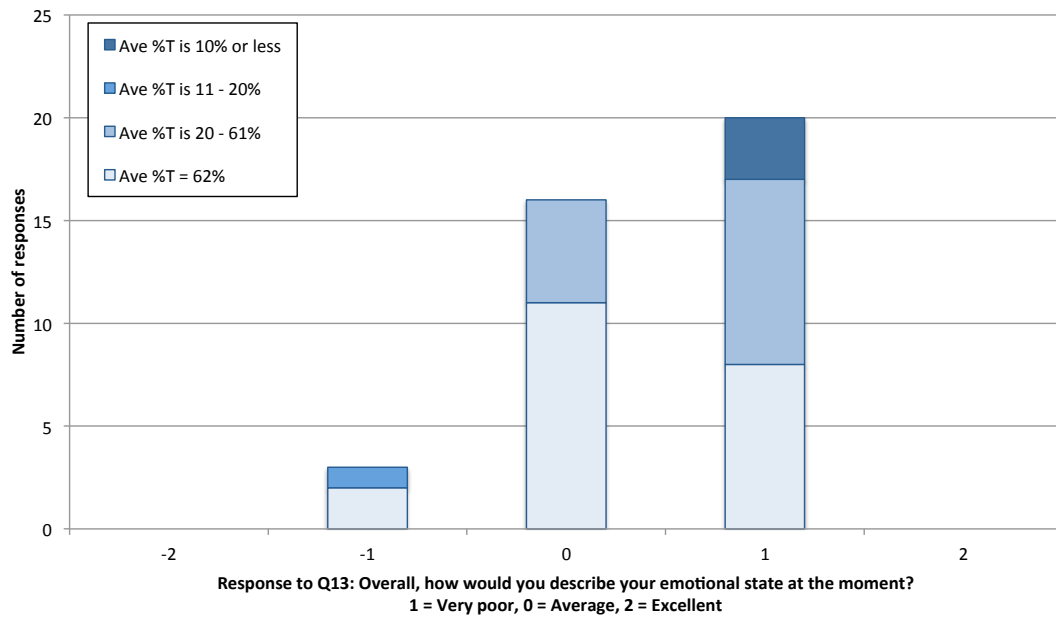
### **9.3 Non-visual effects**

In the questionnaire, participants were asked about their self-reported alertness, emotional state and how pleasant they found the space at that time. The question wording and scales were described in Chapter 5. Figures 9.6, 9.7 and 9.8 show the responses to these questions with the corresponding area-weighted average transmittance of the EC window at the time of response.

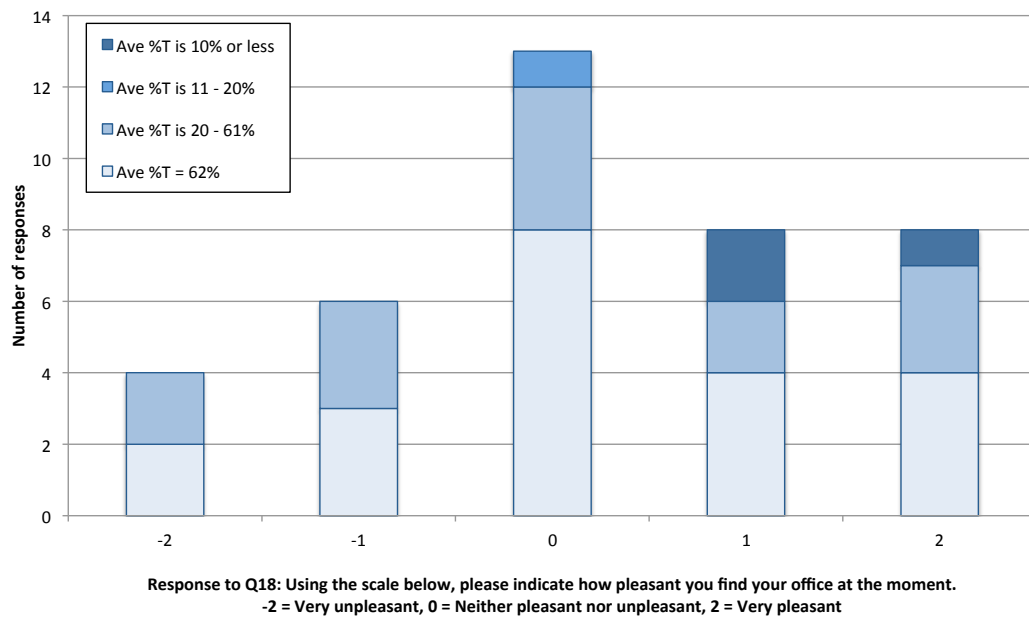


**Figure 9.6 Self-reported alertness level and average EC glazing transmittance at time of questionnaire response**

From Figure 9.6, it can be seen that the majority of responses were in the “Alert” category, and that these responses occurred under a range of window conditions. From these results, there is no discernible relationship between the EC window state and the self-reported alertness of participants. The results of Arsenault *et. al.*’s 2012 study (which used the same scale to measure self-reported alertness) suggested that fixed tinted glazing with a blue colour had the effect of reducing the alertness of participants. This result has not been found here, but this is most probably because of the relatively small quantity of questionnaire data from times when windows were tinted. Furthermore, the blinds were frequently used in room B, for whence most of the questionnaire data came. It would be interesting to repeat this process with more questionnaire data from times when the EC glazing was tinted, and in a room where blind use was minimal, to see if a relationship between the EC window tint and self-reported alertness could be found.



**Figure 9.7** Self-reported emotional state and average EC glazing transmittance at time of questionnaire response



**Figure 9.8** Perceived pleasantness of space and average EC glazing transmittance at time of response

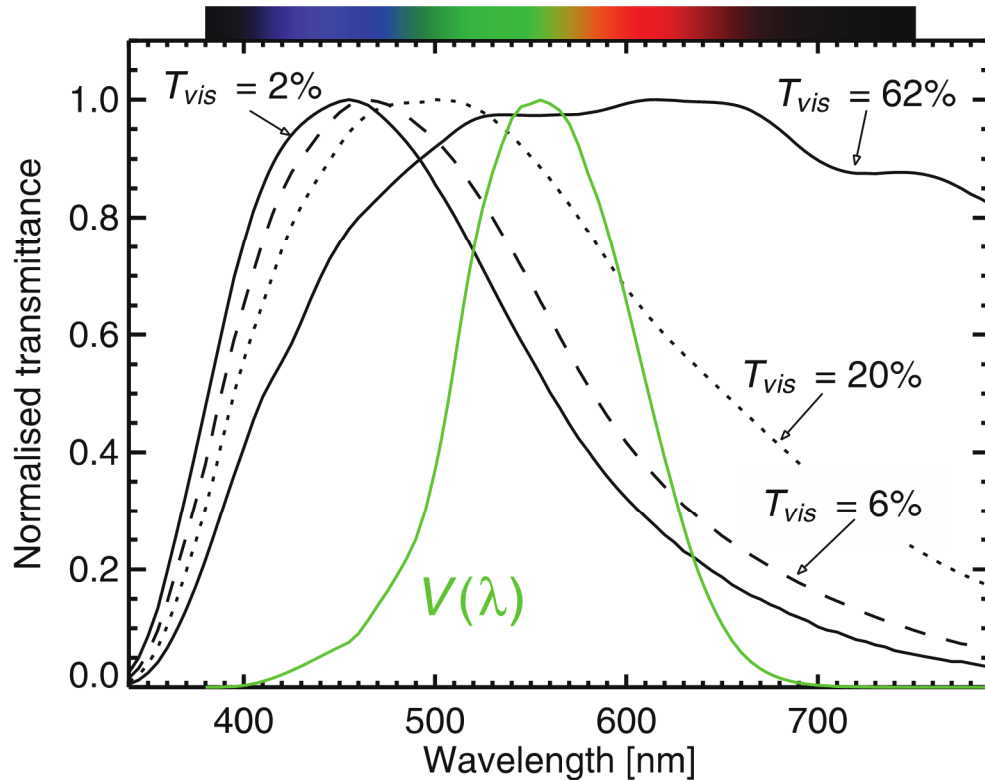
The results shown in Figure 9.7 reveal no obvious relationship between the EC glazing state and self-reported emotional state. Furthermore, the range of responses to this question is quite limited.

In Figure 9.8, it can be seen that some positive responses (to the right of neutral) occurred when the EC glazing was heavily tinted, whilst no negative responses occurred under this condition. This might suggest a tendency for lower EC window transmittance to be associated with higher perceived pleasantness. However, the low numbers of responses when the EC glazing was tinted mean that this result is only indicative of a relationship.

#### **9.4 Daylight spectrum measurements**

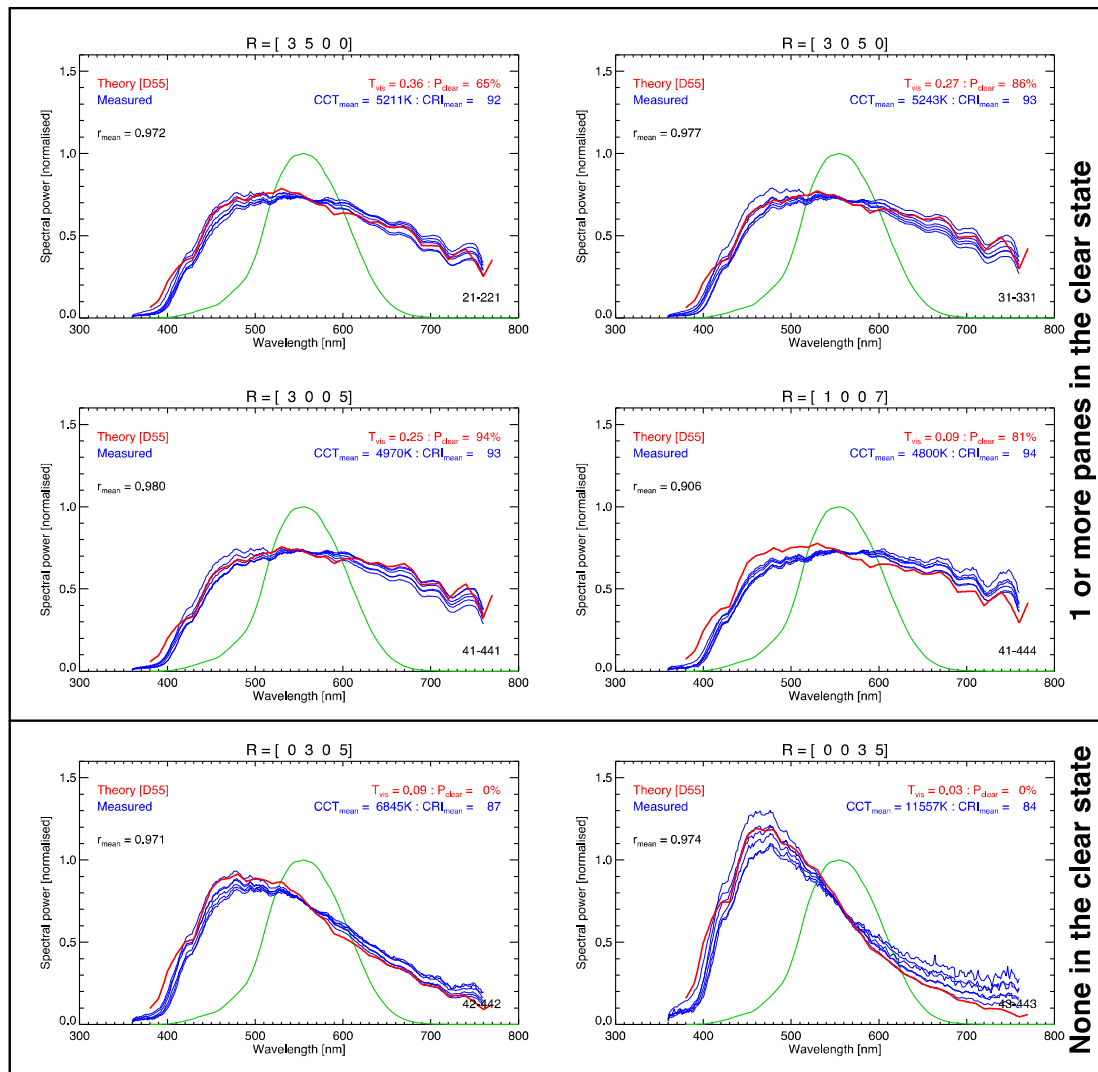
As part of the investigation into the effect of the tint colour on the daylighting conditions within the room, a daylight spectrum study was conducted in 2014. This work was not within the scope of the main PhD study, and was published separately in *Lighting Research & Technology* [Mardaljevic *et. al.*, 2015]. However, as the results are relevant to the research questions about the effect of the EC glazing tint on the appearance of colours in the room, they will be briefly described here.

Figure 9.9 illustrates how the EC window acts as a filter to daylight, distorting the spectral power distribution more as the transmittance decreases. It can be seen that at a transmittance of 2% (*i.e.* fully tinted), the curve exhibits a peak in the blue part of the spectrum. In contrast, at a transmittance of 62% (*i.e.* fully un-tinted), the curve is flatter, with a more even distribution across the visible spectrum.



**Figure 9.9** Normalised spectral transmission curves for the SAGE EC window in its four main states: Fully un-tinted ( $T_{vis} = 62\%$ ), fully tinted ( $T_{vis} = 2\%$ ), and two intermediate states ( $T_{vis} = 20\%$  and  $6\%$ ), where  $T_{vis}$  = visible transmittance. The human visual sensitivity curve  $V(\lambda)$  is also included.

A series of spectrum measurements were made in room B under a range of EC window conditions on a clear, sunny day during the summer of 2013. The results showed that, as long as some portion of the glazing was left un-tinted, the resultant spectrum of daylight in the room was very similar to that when none of the glazing was tinted. Figure 9.10 illustrates the results. The blue curves represent the measured spectra (taken from several positions, hence multiple curves), and the red curves represent the theoretical spectra predicted by a mathematical model, which was based on the area-weighted addition of the power spectra of each glazing condition.



**Figure 9.10** Measured (blue) and theoretical (red) spectrum curves for daylight in the room taken from a range of viewing positions under six different EC window conditions. *Reproduced from [Mardaljevic et. al., 2015].*

Each EC window condition is denoted by the vector  $R = [N_{62} \ N_{20} \ N_6 \ N_2]$ , where  $N_{62}$  = Number of panes with  $T=62\%$ ,  $N_{20}$  = Number of panes with  $T = 20\%$ , etc. (There are a total of eight panes in room B).

It can be seen that, when there are no panes in the un-tinted (“clear”) state, as in the bottom two graphs, the shape of the curve is similar to that of the fully tinted EC window, as shown in Figure 9.9. This is particularly the case for the bottom right graph, in which five panes are fully tinted ( $T = 2\%$ ) and the other three are at  $T = 6\%$ , where the characteristic peak in the blue part of the spectrum is clearly visible. When some panes are left un-tinted, as in the upper four graphs,



the spectral curves are flatter, with a more even distribution across the visible spectrum. These curves are more like that of the EC window in its un-tinted state, as seen in Figure 9.9. It can also be seen that the measured spectra (blue curves) compare very well with the spectra predicted by the mathematical (theoretical) model for each combination (red curves).

The findings of the daylight spectrum study show how the effect of the colour shift brought about by the tinting of the EC glazing can be significantly mitigated by leaving a relatively small proportion of the glazing un-tinted. However, this measurement-based study would be complemented by data collected from human participants under the same conditions, to establish whether occupants' actual perception of colour in the space reflect the measured spectrum results. Even with some zones un-tinted, it is possible that the effect of the blue content in the resultant spectrum might still affect occupants in unforeseen ways. For example, a participants' perception might be influenced by whether or not they can see the blue tint within their field of view.

## **9.5 Exploratory colour discrimination tests**

### **9.5.1 Introduction**

It is widely understood that coloured objects appear differently under different light sources, *e.g.* fluorescent and incandescent. The spectral power distribution of the light source is a key mechanism in the rendering of coloured surfaces. For example, an incandescent source, such as a tungsten filament lamp (or indeed the sun) has a continuous spectrum, whilst other sources, such as LED or fluorescent, tend to have characteristic “spikes” at various points in the spectral curve [Boyce, 2003]. Within the resultant white light of two different light sources, which may appear the same (*i.e.* have the same correlated colour temperature, often referred to in terms of “warm” or “cool” white light), there can be significant variations in the component colour wavelengths, which affect the rendering or appearance of colours illuminated by the source. The Farnsworth-Munsell 100 Hue Test (Figure 9.11) is a tool that was originally developed to diagnose deficiencies in human colour vision (*i.e.* colour blindness)

in the field of ophthalmology, but which has also been used extensively in lighting research to compare colour discrimination under different electric light sources [*e.g.* Boyce & Simons, 1977; Royer *et. al.*, 2012].



**Figure 9.11** Farnsworth-Munsell 100 Hue test apparatus

Given that different combinations of EC window zones in various transmittance states will produce different resultant light spectra, each condition can be considered as a light source with a given spectral power distribution (see Figure 9.9). The effect of the EC window tint on colour discrimination can then be studied using the Farnsworth-Munsell 100 Hue Test.

### **9.5.2 Procedure**

Over two days in May and June 2014, a series of exploratory tests were conducted in room A using participants drawn from university staff, research students and associates (*i.e.* not the normal occupants of room A). A total of five participants gave consent to take part in the study: three males and two females, with an average age of 39.6 years and no reported colour blindness.

The tests were carried out outside of normal working hours, because the tinting and un-tinting of the window would be too disruptive for occupants, and also

because their desk space was required for the test apparatus. The tests were conducted under relatively stable, sunny conditions, to ensure that the spectrum of daylight incident on the windows was as constant as possible during the procedure. (Cloudy conditions can produce a wide range of spectra, depending on the amount of cloud cover, and is subject to change as cloud moves. Furthermore, under cloudy conditions with windows tinted, participants would be unlikely to be able to see well enough to complete the tasks.) In order to ensure that only the effect of daylight entering through the EC window was being measured, the electric lighting in the room was switched off during the tests.

The need to conduct the tests under stable, sunny conditions, as well as outside of normal working hours, made for a challenging set of criteria for research staff and participants. It was necessary to recruit a group of “retained” participants who would endeavour to make themselves available at short notice when the right conditions arose. This is a significant issue when considering future work using occupied rooms such as these.

The test apparatus was placed on the desk of participant A1 and orientated 45 degrees to the window wall, as shown in Figure 9.12. Participants were given detailed instructions about how to use the test apparatus, *i.e.* to arrange the four sets of coloured caps in order of hue (or “shade”). Participants were given two minutes to complete each set. At the beginning and end of each session, the desk illuminance was measured using a hand-held lux meter (LMT Pocket Lux 2) and the spectrum of light entering through the window was measured using a hand-held spectrometer (Lighting Passport by Asensetek).



**Figure 9.12**      **Colour discrimination test set-up**

Tests were carried out for each participant under three EC window conditions, in the following order:

1. Automatic: Upper zones tinted, lower zones un-tinted
2. All zones tinted
3. All zones un-tinted

In test condition 2, all zones were tinted, but not to the lowest available transmittance (2%). This is because, with the electric lighting switched off and all zones fully tinted, there would be insufficient light on the desk to enable participants to carry out the colour discrimination task (Bowman & Cole [1980] recommend a minimum illuminance of 100 lux). Hence, in test condition 2, the upper zones were set to 6% and the lower to 20%. Test condition 1 varied between the two days on which the tests were conducted, as it was determined by the settings of the EC window automatic control system at the time of the test.

After completion of the colour discrimination task, participants were verbally asked three follow-up questions and their responses noted by the researcher. The questions were as follows:

Q1. Did you feel that the test was easier/more difficult for particular window settings?

Q2. Did you find any of the colour strips more difficult/easy to complete than others?

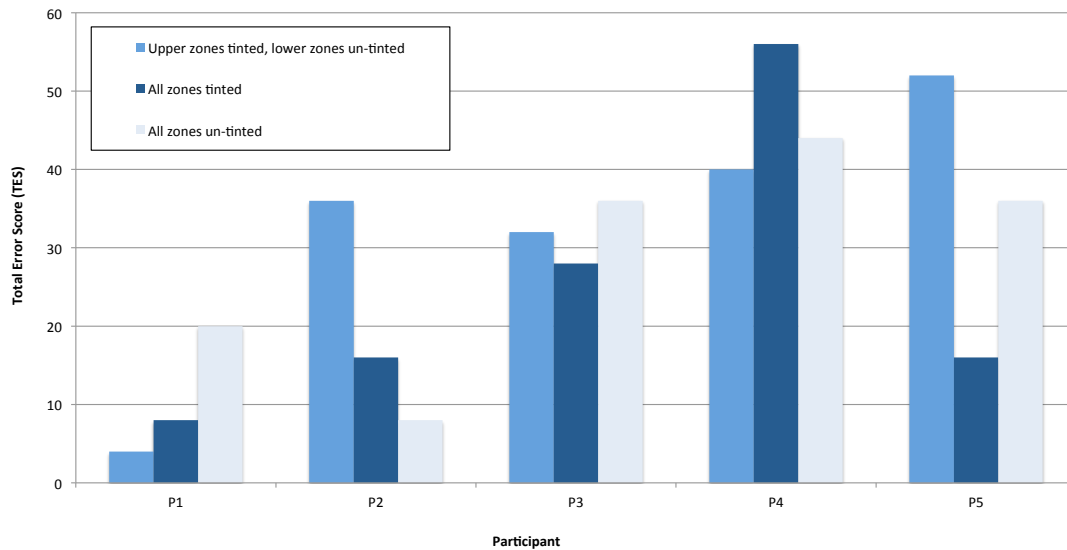
Q3. Did you find that it easier/more difficult to arrange colours further to the right or the left of the strip?

### 9.5.3 Results

Table 9.1 summarises the conditions at the time of each test, and Figure 9.13 shows the 100 Hue Test results for each participant. The Total Error Score (TES) for each participant indicates the degree to which the order of the coloured discs sorted by a participant deviated from the correct order. As such, the TES is inversely proportional to colour discrimination. The software provided with the test apparatus determined that all the scores achieved in these tests fell into the category of either average or superior colour discrimination.

**Table 9.1 Colour discrimination test conditions**

Part.	Gender	Age	Test date	Test condition	Average window %T	Illuminance		Total test duration (mins)
						Start (lux)	End (lux)	
P1	M	49	03/05/2014	1	41%	999	980	19
				2	13%	240	213	14
				3	62%	1,160	1,074	12
P2	M	42	03/05/2014	1	41%	943	970	12
				2	13%	208	194	11
				3	62%	1,206	1,147	11
P3	F	39	06/06/2014	1	34%	950	950	10
				2	13%	370	290	11
				3	62%	11,500	17,000	9
P4	M	33	06/06/2014	1	34%	1,140	970	9
				2	13%	300	260	13
				3	62%	16,000	15,000	9
P5	F	35	06/06/2014	1	34%	940	990	11
				2	13%	260	200	10
				3	62%	50,000	12,400	9



**Figure 9.13 Farnsworth-Munsell 100 Hue test results.**

The results are shown in the order in which the tests were carried out, *i.e.* first with upper zones tinted, lower panes un-tinted, second with all zones tinted, and third with all zones un-tinted. A lower Total Error Score (TES) indicates comparatively better colour discrimination.

It was expected that colour discrimination would improve with decreasing amount of tint, *i.e.* that colour discrimination scores would be generally lower with all zones un-tinted compared with all zones tinted. However, this is not the case. Indeed, from these results, there does not appear to be any consistent relationship between colour discrimination score and the degree to which the EC glazing was tinted. This could be because of the small number of participants in this exploratory study, but it is also likely that test score is influenced by factors other than the EC glazing condition, such as the illuminance at the time of each test, since this could not be fixed. It is also possible that the order in which the tests were carried out may have had an effect on results, *i.e.* due to participants becoming more familiar with the test apparatus and/or due to participants becoming fatigued from the effort of the task. However, a larger study would be necessary in order to quantify these factors.

Another consideration is the effect of mixing zones of different transmittances. As indicated by the daylight spectrum work described in the previous section, even if a relatively small area of glazing is left un-tinted whilst the rest is tinted,

it has a relatively large effect on the resultant daylight spectrum in the space, effectively neutralising the spectrum so that it is similar to that when no glazing is tinted. On this basis, it might be expected that the colour discrimination scores for test condition 1, when the lower zones were un-tinted and the upper zones were tinted, would be similar to the scores for test condition 3, when no glazing was tinted. This effect can be seen in participants P3 and P4, whose TES is similar for test condition 1 and 3. However, the effect is not apparent in the results of the other participants. It would be interesting to see if a similar study with a larger number of participants would provide more evidence for this effect. The responses to the three follow up questions are given in Table 9.2.

**Table 9.2 Responses to follow up questions**

Part.	Q	Response
P1	1	Bright (un-tinted) setting more difficult, particularly the purple colours.
	2	Pink-purple colours easier, apart from under brightest setting. Turquoise also easy, orange-brown most difficult.
	3	No
P2	F1	Un-tinted setting more comfortable, but matching not easier under those conditions.
	F2	Purple easy, green-yellow difficult.
	F3	Left-hand side more difficult.
P3	F1	The third one [un-tinted] was the easiest to conduct the task. The second one [all tinted] was the more difficult.
	F2	Green colours easier; blue/purple more difficult
	F3	No
P4	F1	The darker (more tinted) the setting the more blue/green interference with colour perception.
	F2	The blue/pink was more difficult when glass was tinted
	F3	No
P5	F1	It was more difficult with the darker window setting (this being the bluest window).
	F2	The greens were more difficult compared to the blue and the pink.
	F3	No

The results of the follow-up questions indicate that several participants found the task more difficult when all zones were tinted compared with other conditions. It also seems that some participants found the un-tinted setting more comfortable, but the results in Figure 9.13 indicate that it was not always easier to match colours under this condition. It is interesting that the test scores of the individuals do not often tally with their experience. For example, participant P5 found the task more difficult when all panes were tinted, but achieved a better colour discrimination score under this condition compared with the other test conditions. Participant P3 found the task easiest when all panes were un-tinted and more difficult when all panes were tinted, but their results indicate the opposite, *i.e.* better colour discrimination with all zones tinted than with all zones un-tinted.

## **9.6 Discussion & Summary**

This chapter has brought together various parts of the study, and some additional pieces of work, that were concerned specifically with investigating the effect on occupants of the EC glazing tint colour. A number of items were included in the self-reported data collection (interviews and questionnaires) that were intended to glean information about the effect of the glazing, when tinted, on the following:

- The view through the window
- The appearance of colours in the room
- Various non-visual parameters (alertness, emotional state and perceived pleasantness of space)

In addition to the main data collection, two other pieces of work were described: An exploratory study that tested the colour discrimination of five participants under a range of EC window states, and a daylight spectrum measurement study in which the effect (on spectrum) of mixing tinted and un-tinted panes was quantified.

With regards to the effect of the glazing tint on the view through the window, the interview data were most valuable, and suggested that occupants of both rooms



found that, when windows were tinted, their perception of the sky, weather and time of day was somewhat distorted. The questionnaire data on this subject did not give any insights, possibly due to insufficient data from times when the windows were tinted.

In terms of the effect of the glazing tint on the appearance of colours in the room, again the interview data were more useful than the questionnaire data. The interview data on this subject suggested that many participants felt that, when all panes were tinted, the colours in the room appeared duller, including their colleagues' complexions. However, this issue was not raised in interviews after the control system upgrade, after which the control algorithm was configured so that all zones rarely tinted at the same time (with the lower panes remaining untinted most of the time).

Three items concerned with non-visual effects were included in the questionnaire: self-reported alertness, self-reported emotional state and perceived pleasantness of the space. As with the other questionnaire data, the data obtained from these questions did not reveal any relationship between the EC glazing tint and these non-visual effects. However, this work has shown the potential of using instruments such as these questions in a future study that could be conducted with a narrower focus (on the non-visual effects of EC glazing on occupants), in which a smaller number of questions could be asked more frequently when windows were tinted and with blinds retracted. In such a study, participants might tolerate a greater level of disruption if the data collection programme were shorter or more fragmented, without the continuous presence of instruments and other data collection devices in their workspace.

The results of the daylight spectrum study suggest that if some panes are left untinted, the daylight spectrum in the space is effectively neutralised, making it more akin to the spectrum that would be found if no glazing was tinted. This finding is echoed in the interview data about the effect of the glazing tint on colour appearance in the rooms: After the control algorithm was reconfigured so that all zones rarely tinted at the same time, there were fewer negative comments about the effect of the glazing tint on the appearance of colours in the room. The findings of the daylight spectrum work highlight the potential for a

complementary participant-based study, which could investigate whether occupants' experience of colour in the room would reflect the measured spectrum results.

The results of the colour discrimination tests did not indicate a relationship between colour discrimination of participants and the EC window state. Whilst it is likely that the absence of any discernible relationship is a result of the small number of participants in this exploratory study, it is also possible that colour discrimination might not be the correct measure to use in the study of the effect of the glazing tint on colour perception. There are several other aspects of colour perception that could be investigated, such as colour preference, visual clarity and the significance of colour constancy in how objects are perceived under different EC glazing conditions [personal correspondence with J. Lynes, February, 2016]. The results did hint at the possibility of a colour mixing effect, as found by the daylight spectrum work. That is, the effect of having a mixture of zones at different transmittances, so that the colour discrimination with all zones un-tinted is similar to that when some zones are tinted and some are not. It would be interesting to see if a larger colour discrimination study would provide more evidence for this colour mixing effect. The exploratory colour discrimination tests helped identify many practical issues to consider when designing a larger study.

The work that has been carried out to examine the effect of the EC glazing tint on occupants' experience of colour, view out and other non-visual effects suggests that there is a wealth of information that could be gathered in a larger, more focussed study. The study of colour perception is a large field encompassing many disciplines, and in the context of the wider PhD study, only a limited amount of investigation was possible. Nonetheless, the work carried out so far has revealed the potential for further work in this area and identified several issues for consideration in the design of such a study. This work is discussed in more detail in Chapter 10.

## **Chapter 10**

### **Integrated findings**

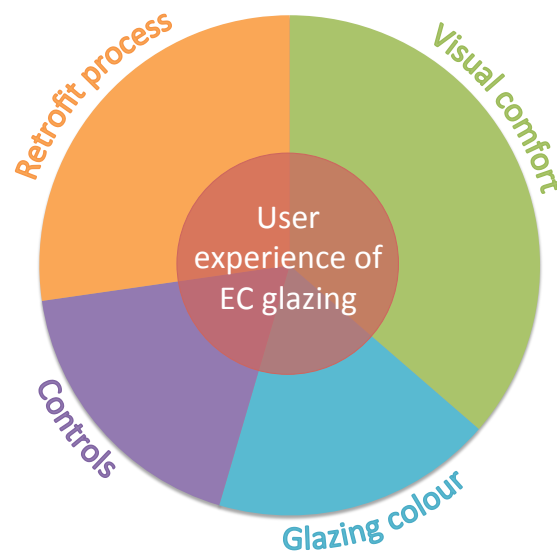
The previous four chapters have described the results of each element of the data collection and subsequent data analysis. In Chapter 6, the EC window retrofit and post-installation period were examined. In Chapter 7, the results of the self-reported data collection were described and analysed to explore links between lighting conditions and occupant perception. Chapter 8 looked at the observed data, which showed how occupants had interacted with the EC windows and blinds to achieve comfortable conditions. Chapter 9 focussed on the effects of the EC glazing tint colour on occupants.

Due to the diverse nature of the various types of data, the structure of those chapters was informed more by the nature of data collected than by the themes of the research enquiry. In this chapter, the results of the previous chapters are drawn together and integrated around the four main areas of research enquiry that were defined earlier in the thesis (Chapter 2). The discussion explores their bases, as well as how they link with established theories about the user acceptance of automated building technologies intended to improve energy efficiency. This is followed by a critical review of the methodology, in which key aspects of the data collection are discussed, in terms of their effectiveness compared with the design intention. A number of recommendations for further research are then made. Finally, the key findings of this study are summarised.

#### **10.1 Findings of the four main areas of the research enquiry**

The research questions, defined in Chapter 2, fall under four main headings: Visual comfort, EC glazing colour, Retrofit process, and Controls. Within each of these areas are a number of more specific research questions, which were used to develop the design of the data collection and inform the data analysis. As the focus of this study is on the user experience with respect to visual comfort, this area contains more research questions than the others. Figure 10.1 (repeated from Chapter 2) illustrates the composition of the research enquiry, and shows

how visual comfort represents a relatively larger share of the enquiry than other aspects.



**Figure 10.1**                      **Composition of the research enquiry (repeated from Chapter 2)**

In the sections that follow, the findings that relate to each of these four main areas will be described.

### **10.1.1              Visual comfort**

The aim of this part of the enquiry was to understand the effectiveness of EC glazing in providing visual comfort for occupants. To do this, it was necessary to look at occupants' first hand perceptions of lighting conditions in the space, when and how often they experienced visual discomfort, the nature and severity of visual discomfort, and how they addressed it.

Key information about how participants perceived lighting conditions and experience of visual discomfort comes from the self-reported data (Chapter 7). Observed data about occupant interaction with the EC manual controls and blinds (Chapter 8) illustrate occupants' typical responses to visual discomfort, and also provide information about the times when visual discomfort occurred,

on the basis that manual tinting of the EC window or lowering of the blinds can be taken as indicators of visual discomfort (*i.e.* visual comfort actions).

It was seen in both the self reported and observed data that the occupants of the two rooms seemed to have contrasting views of the EC glazing, with the occupants of room A appearing to have had a more positive experience than those of the neighbouring room. The observed data showed that, in room A, there were five times more EC manual overrides than in room B. In room B, occupants used the blinds more, with the façade photo analysis suggesting that the blinds in room B covered on average 46% of the glazing, whilst in room A it was 7%. The cross-sectional study of the EC window controls and blinds use data in Chapter 8 further illustrated this, by showing how the occupants of the two rooms responded differently to the same external conditions.

This finding was echoed by the interview data, which revealed a number of themes, one of the most dominant being the general attitude towards the technology. The data from room B indicated a general distrust of the EC windows to provide comfortable conditions, and a preference for using the blinds instead as they were viewed as more reliable. Participants in room B indicated that they felt the response time of the windows was too long and that the tint was not sufficient to adequately control glare and reflections.

In Chapter 7, the relationship between perceived and measured lighting conditions in the space was explored, using the questionnaire responses and corresponding internal or external conditions. The results of the internal conditions analysis indicated the possibility of a relationship between some of the perceived and measured lighting conditions, which were based on HDR-derived luminance metrics. The relationships with the strongest indications are as follows:

- Perceived dominance of daylight in the room increases with increasing mean luminance.
- Perceived dominance of daylight in the room increases with increasing standard deviation of luminance.

This suggests that, as well as mean luminance, the spatial variation of luminance in the room might be an important factor in the perceived daylight level in the space.

In Chapter 8, the observed data were analysed with the corresponding external and internal conditions. In general, the observed data indicated that, in both rooms, there was less visual discomfort in the summer months, based on the fact that there was a marked decrease in the number of visual comfort actions at these times. When visual comfort actions were analysed with the corresponding sun position and façade illuminance, it was seen that, as well as solar altitude, the number of visual comfort actions is related to the stability of external conditions. The results of this analysis suggest that fluctuating façade illuminance is particularly challenging for the EC control system (see Section 10.1.4). Clear *et. al.* [2006] also highlighted the impact of façade illuminance instability on EC glazing effectiveness, and attempted to quantify it using a self-devised Stability Ratio (SR), a measure of the stability of façade illuminance over a given 5-minute period, with larger values indicating more fluctuation. Thus, it was expected that a high SR would be linked with increased blind use. However, the opposite was found, illustrating the difficulty of linking a complex set of external weather-based factors with the experiences of occupants. The internal conditions analysis did not provide evidence for a relationship between any of the HDR-derived metrics and visual comfort actions, but this is more likely to be a reflection of the limitations of the data collected in this study than to suggest that visual comfort actions and measured internal luminous conditions cannot be linked.

These results indicate that, in addition to the technical features of the technology, the effectiveness of EC glazing in providing visual comfort is governed by a number of contextual factors. These relate to both the physical environment and the occupants within it. Yan *et. al.* [2015] highlighted the need to identify contextual factors to understand occupant behaviour with respect to interaction with building components, including shading devices. Shading in particular has been identified as having key characteristics that distinguish it from other systems, such as heating, air conditioning and lighting, [O'Brien, 2013]; primarily, it is the fact that occupants are less likely to return shading to

its former setting (*i.e.* retracted) once the source of discomfort has passed. In addition, there are several psychological mechanisms that can influence an occupants' decision to deploy or retract shading that may have nothing to do with light levels, as noted in Chapter 1.

#### *Factors contributing to the effectiveness of EC glazing*

Using data from the occupants of two rooms who appear to have had contrasting experiences of the technology, it is possible to identify a number of factors that may have contributed to the effectiveness of EC glazing. These are summarised as follows, and fall into two distinct groupings: Physical and Occupant.

##### Physical

- (i) Time of year and weather conditions
- (ii) Furniture layout
- (iii) Technological issues

##### Occupant

- (iv) Trust in technology
- (v) Individual needs in a shared space
- (vi) Impact of the study on occupants

#### *(i) Time of year and weather conditions*

The observed data indicated that there were fewer visual comfort actions in the summer months, suggesting that visual discomfort was experienced more frequently in the winter months, when solar altitude was lower. In both rooms, the number of visual comfort actions peaked in January. This indicates that visual discomfort, and thus the challenge posed to the EC glazing, is strongly related to the time of year and hence the predominant position of the sun. For this façade, with its southeast orientation, the winter months presented a particular challenge because low sun was frequently incident on the windows. Clearly, the orientation of the façade is key, as it will determine the amount of

exposure to solar radiation. In a northerly oriented façade, the sun position and weather condition will not be as important (however, one would question the need for EC glazing on such a façade).

In addition to sun position, the number of visual comfort actions is related to weather conditions; namely, the amount of cloud cover (causing the sun to be visible or not visible) and the stability of those conditions. Fluctuating cloud cover results in unstable façade illuminance, and the increased number of visual comfort actions under such conditions suggests that fluctuating façade illuminance is a particular challenge for the EC control system, due to the non-instantaneous response. This is discussed in more detail in section 10.1.4.

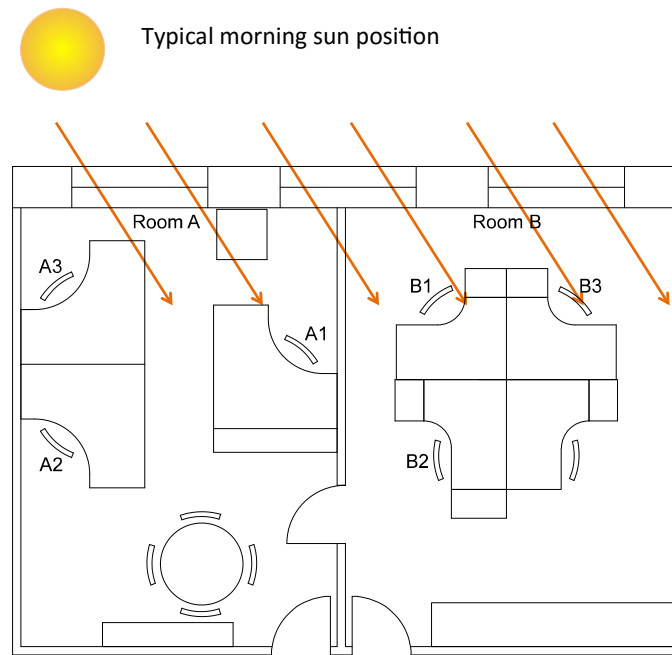
The façade orientation, sun position and weather conditions are the same for both rooms, and thus do not explain the differences in experience between the two rooms. However, it is evident that the same external conditions elicited different responses in the occupants of the two rooms.

## *(ii) Furniture layout*

It is possible that the occupants of room B may have experienced visual discomfort more acutely than in room A because of the differences in furniture layout between the two rooms. The rooms share the same façade, window orientation and interior décor, but the furniture layout is different.

Figure 10.2 shows the desk layout of the two rooms with an indicative typical morning sun position. It can be seen that there are some crucial differences in how the rooms are laid out, making the occupants of room B more susceptible to visual discomfort from direct sun. The desk layout of room A is based on a circulation route through the middle of the room, with desks pushed to the side walls. The desks in room B are arranged in a cluster, with circulation around the perimeter of the room. There are also fewer desks in room A than in room B, allowing participant A1's desk to be located further from the window.





**Figure 10.2** Desk layout of room A & B and typical morning sun position

The furniture layout in room B may have presented a greater challenge for the EC windows alone to provide comfortable conditions compared with room A. Under these conditions, the occupants of room B may have been less accepting of the non-instantaneous response of the windows. In addition, participant B2, who faced the windows, could not tolerate a view of the sun through the window even when the glazing was fully tinted. For this user, the minimum window transmittance was not sufficiently low to adequately reduce the brightness of the solar disc. It is not possible, on the basis of this one occupant (who is also particularly sensitive to glare) to say whether this would also have been the case for other users. Furthermore, it is noted that participant A2, whose position relative to the windows was very similar to that of participant B2, did not report problems with glare, although she did report that she used the blinds on the large window around midwinter, when the sun was at its lowest. A minimum transmittance of less than 1% was recommended by Lee [2006] in order to control the brightness of the solar disc adequately, particularly when views of direct sun are possible from occupants' normal desk positions. At the time of writing, SAGE's latest product has a minimum visible transmittance 1%.

It must also be considered that occupants who can easily change their viewing direction in response to glare may be able to tolerate conditions that would otherwise result in the deployment of shading. In rooms A & B, desktop computers were used, and although the flat screen monitors could be easily adjusted, they appeared to be kept in the same position for the data collection period. Jakubiec & Reinhart [2012] suggested that standard glare metrics might overestimate glare because they are based on a specified viewing direction, whilst in reality humans will re-orientate themselves to reduce the discomfort caused by glare. O'Brien & Gunay [2014] identified interior design as one of the contextual factors influencing occupant behaviour, citing furniture layout and the flexibility of adjustment of seating positions as one of a key aspects. Therefore, as well as the furniture layout, it is important to provide facilities in which occupants can easily change their viewing position.

Of all the factors discussed here, furniture layout is one over which installers can exert some influence, *i.e.* they cannot control the weather or orientation of the building, they cannot control who occupies the rooms, and to a certain extent they cannot prevent technical problems from arising (though they can control how they respond to them). Therefore, furniture layout should be a priority when considering how to obtain maximum benefit from EC glazing. In a retrofit, such as this, it might be less straightforward to propose a new furniture layout in an existing room. However, the potential success of the technology is strongly reliant upon it.

### *(iii) Technological issues*

In the initial period after the EC window installation, there were a number of technical problems that may have contributed to a negative impression about the reliability of the windows, some of which disproportionately affected room B. The most significant of these issues was the defective pane and the delay in replacing it. Other problems, such as sensor positioning, electric lighting system issues and problems with glare mode operation, affected both rooms, but appear to have been tolerated more by the occupants of room A. In room B, the new lighting seemed to cause particular problems for participant B2. Although the

lighting system is separate from the EC windows, it is likely that occupants strongly associated the two systems (*i.e.* new technology in the rooms). Hence, problems with the lighting may have contributed to a general lack of confidence in the EC windows.

(iv) *Trust in technology*

The differences in experience between the two rooms might also be explained by differences in attitude towards new technologies, and in occupants' willingness to engage with the EC windows. In the interviews, some participants from room B used terms such as "unnatural" to describe the EC windows, and indicated that they felt that traditional windows and blinds were "normal" (the implication being that EC windows are abnormal). Participant A1 used the term "modern" in the context of a positive comment about the windows. Thus, the interview data support the idea the participants in each room had differing attitudes towards the EC windows as a new technology in their workplace.

The desire to engage with technology largely depends upon the perceived ability of the technology to benefit the user [Venkatesh, 2000], and users are more likely to engage with a new technology if they have trust in it [Xu *et al.*, 2014]. There are numerous factors that help to build and maintain trust in a new technology, including reliability, validity, predictability and dependability of the technology, as well as early experience of the users [Hoff & Bashir, 2015]. In this study, these issues may help to explain the difference in experience and behaviour between the occupants of room A and B. For example, the technical problems mentioned above, which disproportionately affected room B, could have affected trust development in the early stages. Furthermore, the non-instantaneous response of EC glazing to user inputs could be perceived as a malfunction. Again, this can affect trust in technology, as it reduces "predictability" (the extent to which automation performs in a manner consistent with the operator's expectations) [Hoff & Bashir, 2015].

Hence, in room B, the perceived benefits of using the EC window manual controls to provide shading may have been outweighed by the availability of blinds; a

familiar alternative to the new technology. It was noted by Norman [1994] that for an automated system to provide comfort, the user must gain confidence in the technology, which can take time to develop, especially where there is fear and suspicion about the capability and actions of “agents” or automata. Norman also highlighted the tendency for exaggerated expectations of such technology, in part due to the human tendency to anthropomorphise any technology that seems in the least bit intelligent. As he puts it: “Have a system act as if it has its own goals and intelligence, and one expects full knowledge and understanding of human goals.” This phenomenon may even be reinforced where automated building systems are labelled as “intelligent” or “smart”, which is the case with EC glazing. Thus, occupants may have expected the windows’ automated control mode to be well attuned to their needs, and when they found that this was not the case, were disappointed with the technology.

*(v) Individual needs in a shared space*

The rooms were populated by groups of different individuals, each with their own needs. Visual discomfort is a highly subjective phenomenon, so it is not surprising that the same external conditions elicit different responses from individuals. The effect is arguably more pronounced in room B, because this room had an occupant (participant B2) with different needs than the others, due to her health condition. She also faced the window and was therefore more likely to experience direct sun in the eyes. It is possible that participant B2’s needs may have been the overriding factor in decisions about lighting levels, window tinting and blind positions in room B. Occupants in shared workspaces often consider the comfort of their colleagues as well as their own when making adjustments to their environment, and in particular, shading. Thus, if an occupant wishes to make an adjustment, they must do so in a way that does not breach the consensus of the group. O’Brien & Gunay [2014] identified social constraints as a contextual factor influencing occupant interaction with systems such as shading, particularly in shared offices where multiple occupants with different preferences must often endure similar environmental conditions, and where the actions of one occupant to achieve comfort may be perceived as a violation of

social norms. It is also possible that participant B2's dissatisfaction with the EC windows might have influenced the views of the other occupants. As others' views began to align more with participant B2, a possible "bandwagon effect" may have magnified it, whereby the prevailing opinion is adopted by all members of the group [Asch, 1955].

*(vi) Impact of the study on occupants*

Although this is not an issue that would generally affect installations of EC glazing, it is important to note the possible impact of study participation and the presence of data collection equipment upon the attitude of the occupants towards the technology.

The study itself may have had a greater impact upon the occupants of room B, because there were more participants in room B than in room A, and thus participants in room B may have been more likely to become fatigued by the activities associated with their participation in the study. Participant fatigue [*e.g.* Krosnick, 1999] is a significant issue in data collection, and was carefully considered during the design of the study, as explained in Chapter 5. Despite this, however, some participants in room B expressed a feeling of weariness with the study, primarily due to its duration, as described in Chapter 7. Comments suggested a feeling that the study had gone on too long, and that some aspects of the data collection were too onerous. In contrast to this, aside from the initial increase in visitors to the room and the presence of the HDR camera early in the data collection, the room A participants did not indicate that they felt the data collection to have been a burden, nor that the duration of the study was an issue for them.

The possible impact of the self-reported data collection upon occupants is also worthy of consideration. As three of the main participants were in room B, this is also an issue that may have disproportionately affected that room. Furthermore, their contributions to the self-report data collection were significantly greater than that of the participants of room A. Participant A1 contributed a relatively small proportion of self-reported data, and whilst the additional participants

from room A (A2 and A3) were occasionally asked for informal feedback during researcher visits, and included in the last set of interviews, they were largely “left alone” during the data collection, since they had not agreed to be full participants. As a result, perhaps they were freer to experience the EC windows without being regularly asked for their opinion.

In addition to the active aspects of study participation, there is a passive, but nonetheless important, aspect: the presence of monitoring equipment in room B, which may have been a constant reminder of the study, even when participants were not being asked for their views. For a number of reasons, room B became the focus when considering where to locate monitoring equipment. There were two HDR cameras located there for almost 18 months, taking images every 30 minutes throughout each day. In room A, there was only one camera, and for the majority of the data collection period, this was only located in the room for some two-week periods, due to a lack of space in the area. The cameras were arguably the most obtrusive items, because of the “shutter” noise they generated as well as their physical size. There were many occasions when a HDR camera stopped working, requiring a visit to the room to investigate the problem. There are also the inescapable connotations with “being watched”, and this may have played a part in the experience of the room occupants, despite efforts to reassure them that the images were being captured purely to study the luminous environment. Concerns of privacy were noted by Newsham & Arsenault [2009] as an issue when using cameras for the monitoring or control of lighting conditions in workplaces, who concluded that more work was needed to identify ways to change the appearance of cameras used for this purpose so that they are not identified as such by occupants.

In addition to the cameras in room B was the illuminance monitoring apparatus (illuminance meter and sensors), which proved to be very problematic throughout the study. As a result, visits to reset the device were a regular occurrence throughout the data collection. Regular visits to access the EC control system laptop were also required early in the data collection, until remote access was established. The presence of other monitoring equipment, such as Hobo

loggers, is not considered to be a factor, since they are physically unobtrusive and were present in both rooms.

It is probable that, for at least some occupants, technical issues with the monitoring equipment were conflated with the reliability of the EC windows, thus contributing to a negative perception about the technology. The presence of the equipment, combined with regular researcher visits to room B to fix problems, may also have contributed to a feeling that they were part of an experiment, rather than that they had benefitted from an upgrade or enhancement to their office facilities. In the final interview, one of the room B participants (B3) used the term “guinea pig” to describe how she felt in relation to participating in the study. This may have contributed to a perception that the EC windows themselves were experimental (*i.e.* a prototype), and thus unreliable, rather than a fully-fledged product.

Conversely, in room A, there were fewer researcher visits to the room, and very little monitoring equipment except for periods when the HDR camera was installed. Aside from the technical performance of the EC windows, there was little to undermine the confidence of these occupants about the reliability of the technology.

### *Summary*

The factors described above have been identified as contributing to the effectiveness of EC glazing in providing visual comfort for occupants. They relate to both the physical environment (weather and season, room layout, technological issues) and the occupants (trust in technology, individual needs, study participation). O'Brien & Gunay [2014] proposed nine contextual factors that contribute to adaptive occupant behaviours with respect to automated and manual building systems, and there is considerable overlap with the factors found here. In particular, interior design, which includes furniture type and layout, was identified by O'Brien & Gunay as being an important determinant of occupant behaviour. Social constraints, particularly within a shared office space, were also noted as one of the contextual factors. Given that O'Brien & Gunay's list

is intended to apply to a range of automated and building systems (*e.g.* heating, lighting, air conditioning), it is pertinent to note that EC glazing presents its own unique challenges: It has many of the characteristics of an automated shading system, but behaves in a way that is not familiar to typical building users and has a striking aesthetic (*i.e.* the tinted glazing colour) that may induce a strong polarised response in users. Thus, the success of EC glazing relies more heavily on user trust and acceptance in the technology compared with other, more familiar, systems.

### **10.1.2 EC glazing colour**

This aspect of the research enquiry investigated what effects the colour of the EC glazing, when tinted, might have on a variety of perceptual aspects. These include the perception of colours in the rooms, how the view through the window is affected, and whether the tint colour affects the occupants in other, non-visual ways: alertness, emotional state and how pleasant the room appears. The data needed to answer these questions comes from the self-reported data (interviews and questionnaires), as well as from some separate experiments that were carried out to explore these issues further. The results were described in detail in Chapter 9.

Responses to questions about the view through the window and the perception of colours did not lead to much insight, since a considerable proportion of the questionnaire responses were completed at times when the windows were not tinted. Three items were included in the questionnaire in order to assess some non-visual effects of the glazing colour: self-reported alertness, self-reported emotional state and perceived pleasantness of the space. The data obtained from these questions did not reveal any relationship between the EC glazing tint and these non-visual effects. However, the work has indicated the potential of using a technique such as this in a future study, particularly one that is primarily focussed on the effect of the EC glazing colour on occupants.

The interview data suggested that occupants of both rooms found that, when windows were tinted, their perception of the sky, weather and time of day was



somewhat distorted. The data also suggested that many participants felt that the colours in the room appeared duller, including their colleagues' complexions. Previous research on the effect of different glazing colours is limited, however, it is noted that Bulow-Hube [1995] found that coated and multiple-pane glazing (with a reduced transmittance) resulted in colours being perceived as duller and the room more enclosed. She also commented that the sky, when viewed through such glazing, might appear darkened, so that the perception of time and day and weather conditions are distorted, *e.g.* cloud looks darker and more likely to produce rain. Zarkadis & Morel [2015], who studied EC glazing that also had a blue tint colour, found that the majority of their (nine) participants perceived colours in the room and the view out to be unnatural, especially when the windows were fully tinted.

The perceived dulling of colours and complexions was reported less after the control system upgrade, when the control algorithm was configured so that the lower panes remained un-tinted most of the time. This highlights the importance of the EC window zoning, since it allowed upper and lower zones to have different control settings so that all zones rarely tinted simultaneously, and the perceived effects of the glazing tint colour were mitigated. This finding was supported by the results of a study of the daylight spectrum, which strongly suggested that if some panes are left un-tinted, the daylight spectrum in the space is effectively neutralised, making it more akin to the spectrum that would be found if no glazing was tinted [Mardaljevic *et. al.*, 2015].

A series of exploratory colour discrimination tests were carried out under different window conditions, but the results did not indicate a relationship between participants' ability to discriminate colours and the EC window state. This might be due to the small number of participants in the study, and it is also possible that colour discrimination might not be the correct measure to use. Nonetheless, this work helped identify a number of practical issues to consider when designing a larger study. This is discussed in more detail in section 10.4.

### **10.1.3 Installation and commissioning**

At the outset, this retrofit was seen as a valuable opportunity to document the experience of installing and commissioning EC glazing in a retrofit application, it being the first of its kind in the UK. As a novel glazing technology (to the UK market), it had many features that differentiated it from traditional windows and would thus affect the installation process. Furthermore, the reactions of occupants during the initial period following the installation were key to understanding how this technology could be applied successfully in future.

In Chapter 6, it was explained how the EC glazing installation and commissioning highlighted a range of practical issues. From these, a number of recommendations can be made for future installations, particularly retrofits. Below is an abbreviated version of the recommendations made in Chapter 6.

#### *Prior to installation*

- Communication between manufacturer, client and installer is key, and should commence well in advance of the installation, so that the installer is clear on what is required, and the client knows what to expect from the system and has agreed the locations of any hardware associated with the installation.
- If resources allow, the windows and hardware should be shipped to site in advance so that they can be connected and checked to see that they are functioning properly prior to window installation to avoid the installation of malfunctioning parts.
- If a daylight-linked electric lighting system is not already in place, the lighting should be upgraded to take full advantage of the potential energy savings brought by the installation of EC windows.

#### *During installation:*

- Both the manufacturer and the client should be represented on site during the installation.

*After installation:*

- Building owners and occupants should be fully briefed to ensure that they know how to operate the system and to ensure that post-installation changes (such as the introduction of new furniture or equipment) do not hinder the proper functioning of the windows or access to the manual controls.
- On-going remote access to the control system is recommended, so that system settings can continue to be adjusted by the window manufacturer or the client. This ensures optimal performance throughout the seasons and in response to changes to the building, such as changes of use or personnel.

#### **10.1.4 Controls**

There are several aspects to the EC window controls. First, there is the user experience of the control interface itself, *i.e.* for manual control. Then, there is the behaviour of the system in different control modes, *i.e.* how it responds to changing external conditions in automatic mode, and how it responds to manual control inputs from occupants. Lastly, there is the question of what can be learned from the process of refining the control system settings to suit the site and users over an extended period.

##### *Users' perceptions of the control interface*

The interview data (Chapter 7) indicated that most occupants found the control interface to be easy to use. The design of the interface is reasonably simple and intuitive, with the up and down arrows corresponding to increasing or decreasing tint (shading), as shown in Chapter 4. Simplicity and transparency of controls interface design has been identified as key to user acceptance [*e.g.* Galasiu & Veitch, 2006; Ylmaz *et. al.*, 2015]. Furthermore, it is noted that the EC window manual controls were a new addition to the occupants' rooms, *i.e.* not a replacement of existing familiar control elements, such as lighting or air conditioning. The users' thus had no past experience of such controls and no

reference for comparison, and were unfamiliar with the entire concept of “dimming” a window. Therefore, it could be argued that the simplicity of the control interface design in this case was even more important.

Some occupants in room B indicated that they would like to be able to control the windows remotely. Whilst this may have been impractical to implement in the shared offices in this study, this user feedback may have implications for the design of the control interface. It is noted that these comments were made only by participants in room B, who rarely used the manual controls. Most of the manual overrides occurred in Zone 2, the lower portion of the large window in room A. The participant who sat nearest to this window (and the most prolific user of the manual controls) could reach the controls without leaving her seat. O’Brien & Gunay [2014] noted that accessibility of personal control is an important determinant of user interaction with building systems. Sutter *et. al.* [2006] found that remotely controlled shades were used three times more often than manually controlled versions. Thus, it is possible that, for some occupants, the inconvenience of having to get up to use the controls outweighed the perceived benefits.

Data about occupant interaction with the EC window manual controls (Chapter 8) showed that the intermediate tint settings were rarely used in either room. This suggests that the control interface could be simplified so that it allows users to fully tint or un-tint the glazing, perhaps with only one intermediate setting.

Room B participants indicated that one of the reasons they rarely used the manual controls was because the response time of the windows was too long (Chapter 7). The manual control use data showed that manual inputs (in both rooms) typically occurred in clusters (Chapter 8), where a user had repeatedly pressed the same button. This behaviour may indicate a degree of user frustration, induced by the fact that the windows do not visibly respond immediately. It also may have contributed to a lack of trust in the technology (see section 10.1.1) due to the perception that the windows were not functioning properly.

The interface used in this study indicates to the user that the manual input has been registered by the system by moving the indicator light up and down, to

show that more or less tinting has been requested. However, as the glazing takes some time to reach the desired state, an interface that includes another form of feedback would be beneficial to reassure the user that the system is responding, for example using a flashing indicator light. O'Brien & Gunay [2014] identified transparency of automation systems as a key factor affecting occupant behaviour, recommending control interfaces that clearly indicate that the system is responding to a manual command. This issue was also highlighted by Lee *et. al.* [2012] in their analysis of EC window manual controls usage data over a six-month period. Nonetheless, the importance of simplicity in the interface design, as mentioned previously, should take precedence.

### *Control system response*

Chapter 8 included an analysis of control system behaviour around the times when blinds were lowered and manual overrides occurred. The results indicated that in many cases, spikes in the façade illuminance had occurred around these times. These spikes were apparently severe enough to cause visual discomfort for an occupant or occupants, based on the fact that a visual comfort action was taken, but did not trigger a response in the automatic control system. This suggests that the control system “dead-band” of two minutes, designed to avoid rapid changes in the glazing tint in response to rapid fluctuation in façade illuminance, may need careful consideration. These momentary spikes in façade illuminance are not sustained enough to be recognised by the automatic control system, but human occupants may not be so tolerant where visual discomfort is concerned, especially if the ability to continue with a visual task is compromised. Glare mode might go some way to addressing this issue, however, it is also subject to the two-minute delay, and as such may not be triggered quickly enough by momentary spikes in façade illuminance.

### *Optimisation of the control algorithm after installation*

The control system was refined via an iterative process of adjustment in response to feedback from the users and direct observation. There were some

problems acquiring data from the control system during the first seven months after installation, which made it difficult to test the effect of new settings on control system behaviour. Thus, occupant feedback became the most important tool in the process. During this period, the threshold settings, which dictated when the glazing would tint in automatic mode, were changed several times in response to occupant feedback. In March 2013, the control system was upgraded to the latest available version. This resolved a number of issues, including problems with glare mode and data acquisition. The new control system provided logged information in a much more accessible format than the previous one.

Had control system data been more readily available during the first few months following installation, the refinement process may have been based upon the number of manual inputs to the system as well as feedback from occupants, on the basis that a higher number of manual overrides indicates that the control settings need further refinement. However, the self-reported and observed data collected in this study indicated that satisfaction with the EC windows was higher in room A, where the EC manual controls were much more frequently used. In room B, the EC manual controls were hardly used, but rather than indicate satisfaction with the EC windows, this lack of interaction was a result of disengagement with the EC manual controls in favour of the blinds as the primary method of glare control. This suggests that, when blinds are available, it should not be assumed that fewer manual overrides is an indicator of satisfaction with the control system settings.

Whilst the duration of control system refinement was probably longer than would be typically necessary (due to data acquisition problems, etc.), the experience from this study suggests that a period of at least six months should be allowed for control system adjustment. A six-month period also allows a full range of sun positions and weather conditions to be tested. Furthermore, the time of year when the installation takes place may be important for control system refinement; a summer installation has the advantage of allowing occupants to become familiar with the technology under less challenging conditions before the sun altitude decreases in winter.

Feedback from occupants in room B indicated that when all the zones were tinted, they felt that the room appeared “too dark” or “blue”. In response to this, further changes were made to the control system settings once the new control system was in place. The lower zones (2, 4, 6 & 9) were given higher upper thresholds to make them less sensitive than the upper zones. Glare mode was only assigned to the upper zones so that the lower row of panes was tinted less often. A further adjustment was made to the glare mode settings in October 2013. The upper glare mode threshold was decreased to trigger glare mode at a lower façade illuminance, and the lower threshold was also decreased, so that the system remains in glare mode for longer. The interview data (Chapter 7) indicated that participants in both rooms felt that the zoning of the windows was a useful feature, because it allowed the upper and lower portions of the windows to have different control settings, so that the lower zones were less sensitive and tinted less often. After the control system upgrade, when these settings were put in place, participants made fewer negative comments about the affect of the glazing tint colour on the appearance of colours and colleagues’ skin tones (see section 10.1.2).

Hence, the division of glazing into multiple zones has many advantages. The only disadvantage may be the increased number of manual switch units that are required. In this study, participants were not asked for their views on the number and locations of switches, so it is only possible to speculate. However, in buildings with highly glazed façades, there may be fewer logical positions in which to locate switches, and as such their positions should be carefully considered.

### **10.1.5 Summary**

The aim of this study was to evaluate the user experience of EC glazing in a real-world setting over a longitudinal period. The research questions focussed on visual comfort, in addition to the occupant experience of the controls (interface and automated response), the effects of the glazing tint colour and the lessons to be gained from the experience of the retrofit installation. EC glazing is a novel technology that is unfamiliar to typical building occupants, with striking

aesthetic characteristics owing to the colour of the glazing when tinted, and thus presents a new challenge when considering the factors that influence its successful implementation. A number of factors that affect the ability of EC glazing to meet the visual comfort needs of occupants have been identified, and these resonate with existing theoretical frameworks, such as that put forward by O'Brien & Gunay [2014]. Several recommendations have been made with regards to the design of the control algorithm and controls interface, and relating to the installation and commissioning of the control system. A range of aspects relating to the effects of the glazing tint colour on occupants has been investigated, highlighting the need for further research in this area. The key findings resulting from the study are summarised in section 10.4.

## **10.2 Methodology review**

It is instructive, at the end of any piece of research, to consider whether the methodology fulfilled its intended purpose. In real world research, it is common for unforeseen circumstances to prevent the data collection from proceeding exactly as planned (hence the need for a flexible design). In cases where the data collection did not produce the desired result, it is useful to consider how it could be carried out more effectively in future. In the following sub-sections, key aspects of the data collection will be discussed in turn.

### **10.2.1 Real-world research and the mixed methods approach**

The data collection in this study used a combination of self-reported, observed, and measured data to answer a number of research questions about the user experience of EC glazing, as illustrated in Table 5.2. The scope and design of real-world studies is strongly informed by practical constraints of the study setting. One of the most crucial aspects is participant engagement, especially in studies with low numbers of participants. In this study, the data collection was designed to respect both the need for data of sufficient quality and the need to maintain the engagement of participants. For example, data capture was automated as much as possible to avoid disrupting participants' work tasks, but contact with



them was also essential to avoid dissatisfaction and the risk of non-participation. The deployment of additional simple tools, such as the daily experience record sheet, required minimal time investment from the participants, but still provided useful coarse feedback. It also allowed occupant satisfaction with both the EC glazing system and the research study itself to be monitored, so that problems could be resolved in a timely manner. Participants appreciated that their feedback was taken into account and acted upon quickly, which helped to reduce participant burden and facilitated engagement throughout the monitoring period.

In lab-based studies involving time-limited experiments, the expectations of the researcher and participant are arguably easier to manage, especially if participants are compensated for their time. In real-world research, participant recruitment can be more complex, because it can be difficult to give a potential participant a realistic idea of how disruptive participation might be without discouraging them from agreeing to take part. Furthermore, at the outset of a long-term mixed method study, researchers may not yet fully know how disruptive the process will turn out to be, whatever their intentions. Thus, the management of participants' expectations became an on-going process throughout the data collection.

By using a combination of methods with different depths of enquiry over a longitudinal period, detailed data were collected about the experience of these users. The observed data (about occupant interaction with blinds and EC window controls) proved to be very useful, since they indicated the times when occupants were experiencing visual discomfort and how they chose to resolve it. These data were reinforced by the interview data, which allowed the motivations behind the visual comfort control behaviour to be explored. Thus, the observed and self-reported data were mutually complementary, and allowed the triangulation of data about the user experience.

In the following sub-sections, key elements of the data collection will be reviewed.

### 10.2.2 Questionnaires

The questionnaires were intended to capture data about occupants' perceptions at a specific moment in time, to enable links between measured conditions and subjective occupant experience to be investigated. Questions covered a range of topics; primarily relating to lighting conditions (perceived light levels, quantity of daylight, experience of glare and reflections) but also to thermal conditions, view through windows, appearance of colours, emotional state, alertness and general impressions about the room. However, the ability of the questionnaire data to relate physical and subjective parameters was limited by a number of factors, which are explored below.

#### *Conditions at times of questionnaire response*

Participants were asked to complete questionnaires at a time convenient to them during a two-week period. This strategy was adopted because it reduced the potential for participants to feel burdened by requests to complete questionnaires, and because it was expected that a "randomly" dispersed selection of response times would represent a range of external conditions and thus window states. When the questionnaire data were analysed, it was found that over half had been completed when conditions were cloudy and the EC windows were un-tinted. For the most of the other half, the glazing was partly tinted, and in a small proportion of cases all the glazing was tinted. This does represent a reasonable range of external conditions and tint states. However, in room B, from where most of the questionnaire responses originated, the blinds were regularly used. This meant that questionnaire items that were designed to capture information about the effect of the glazing tint (for example, on the appearance of colours in the room) were not as effective as anticipated.

In future studies of variable tint glazing, it would be valuable to consider whether a time-linked questionnaire is intended to measure the effect of the glazing on various parameters when tinted, or over a range of tint states. If it is the former, then questionnaire responses should be requested under specific conditions, *i.e.* under sunny conditions, when glazing is tinted. It would also

require that blinds, if present, were fully retracted at the time. This approach would require participants being asked to complete a questionnaire immediately, which may not be convenient to them. With this in mind, the length of the questionnaire should be kept to an absolute minimum to reduce the potential disruption. In addition, participants should be given the option to defer the questionnaire for a short period (say, 30 minutes), as in Painter *et. al.* [2009].

#### *Moment-specific self-reported data*

Participants were asked to respond to each question with respect to their perception at that very moment. However, it must be acknowledged that participants may not be able to accurately report how they feel at a precise moment in time without being biased by previous experience or mood at the time of response [Robson, 2002]. The attitude of the participant towards the study itself could also be a factor, *e.g.* a participant might be more inclined to respond negatively to a question about perceived lighting conditions in the space if they are fatigued from answering questions of this nature. The question of how well self-reported data can reflect reality highlights the importance of observed data and the triangulation of multiple sources [Yan *et. al.*, 2015], the approach used in this study.

### **10.2.3 Capturing blind use**

One of the main aims of this study was to learn about the effectiveness of EC glazing in providing visually comfortable conditions for occupants under a range of external conditions. However, given that one occupant had a visual condition that made her more sensitive to glare, and since the ability of EC glazing alone to provide adequate shading in this location was unknown, it was necessary to provide blinds for occupants in addition to the EC windows. In this study, it was essential to provide occupants with the means of controlling their environment to meet their comfort needs at all times, so that they could continue to carry out their work tasks. If the comfort of occupants or their ability to work were to be compromised by the study, it could put at risk the entire data collection.

### *Retention of blinds after the window retrofit*

During data analysis, the presence of blinds in the study meant that blinds use data had to be considered in conjunction with EC window data (*i.e.* as visual comfort actions). Otherwise, the results could be misleading, *e.g.* when façade illuminance was high, but participants reported satisfactory lighting conditions in the room, one could wrongly conclude that the EC windows were effective at providing visual comfort in those instances. However, by examining external conditions and EC window control system data around the times when blinds were lowered, a greater understanding of the visual comfort needs of occupants was achieved, since it identified instances when the EC glazing alone appeared not to meet the visual comfort needs of occupants.

### *The blinds diary and façade photos as a means of recording blind usage*

The blinds diary proved to be a very useful device for capturing blind use. It was simple and easy for occupants to use, and did not require additional technology to be installed in the space. However, as it was not automated, it was dependant on occupants filling it in every time they lowered a blind, and recording the time accurately. The time recorded by an occupant may have been derived from a number of sources, which may or may not have been accurate, *e.g.* wall clock, wristwatch. The data in the diary were checked against HDR images, and this verified that the diary entries were a good reflection of reality. There were a few occasions when blinds were lowered but occupants did not fill in the diary. No blinds diary entries were made in the at all in room A, with occupants citing a lack of blind use as the main reason, which meant that there were no detailed blinds use data for room A. However, the façade photos did provide supplementary information about the general pattern of blind use in that room.

As blinds were not retracted at the end of each working day, the blind use data did not account for every instance when conditions were such that extra shading was required. At the time when the blinds diary was introduced, however, this requirement was deemed to be too onerous for participants, considering the burden already imposed upon them by other aspects of the study, *e.g.*

questionnaires, interviews, completion of daily experience sheets, completion of the blinds diary, tolerance of the HDR cameras and associated equipment.

Automated façade photos could provide accurate blind position data that could be systematically analysed using software. However, this would require the installation of cameras in an adjacent building with an unobstructed view of the façade, and could not be implemented in this study because a suitable location for such a camera could not be identified. Furthermore, this method would not resolve the issue of blind retraction at the end of each day. Motorised blind control would resolve both of these issues, by automating the recording of blind activity and by enabling blinds to be automatically retracted at the end each day. However, the addition of motorised blinds could result in significant additional cost, and would add another layer of complexity to the installation process, as well as the hardware required (*e.g.* additional wall switches).

#### **10.2.4 HDR data collection**

HDR images were captured every 30 minutes throughout the working day as a way of recording the luminous conditions in the rooms, and particularly using luminance-based parameters, since these are considered a useful indicator of the perception of occupants.

##### *Camera positions*

Previous research using HDR images typically located cameras to match, as closely as possible, the normal viewing position of an occupant. This enabled view-dependent metrics (such as DGP) to be linked to occupant experience. However, for a longitudinal real-world study such as this, it was not possible to locate cameras at or very close to occupants' head positions, even for short periods.

In room B, two cameras were located at approximately the eye-height of seated occupants to capture a general view, in locations where they were unlikely to cause an obstruction. Although the HDR images did not capture the field of view of each occupant, it was found that the general view of the room in two lateral

(*i.e.* parallel to the window) directions was very useful at capturing conditions in the room. These positions had the added advantage of including a view of the windows, thus allowing blind positions, window states and external conditions (*e.g.* the presence of direct sun) to be checked against other data sources. In room A, it was less straightforward to find a location for cameras. As there was only one participant in room A, only one camera was placed in the room. A position close to her normal viewing position was found, but it caused an obstruction and eventually had to be removed apart from two-week periods around the equinox and solstice. The experience in room B indicates that in longitudinal studies such as this, camera positions that are at occupants' eye-level and give a general view of the room, include the windows, can be very useful, and that unless view-dependent metrics are being studied, it might not be necessary to locate cameras at or near occupants' head positions.

As part of the investigation of possible camera positions before the EC window installation, a series of test HDR images were taken at the workstations of participants during periods when they were away from work (*e.g.* on annual leave or after work hours), with cameras located at the eye position of the participant. The main purpose of this exercise was to allow differences between the images taken in the final camera positions and the "ideal" camera positions to be compared. However, the use of blinds in room B, where two of the cameras were installed for the entire data collection, made it difficult to link HDR data with EC window state and external conditions, and hence this comparison was not carried out.

### *HDR capture interval*

HDR images were captured every 30 minutes. This interval produced a manageable flow of data (*i.e.* file sizes) and limited the potential disturbance caused by the noise of the camera shutter during the capture process. Nonetheless, this interval means that a gap of up to 15 minutes was possible between HDR capture and occupant action (visual comfort action or questionnaire response). On days with fast-moving cloud, the luminous conditions can change significantly within minutes. Hence, the conditions

captured by a questionnaire response might be different from those captured by the closest HDR image. A smaller capture interval would reduce this potential time gap, thus increasing the likelihood that the same conditions were being measured by both instruments. However, it could generate a very large volume of data, requiring significant resources for HDR data handling, storage and analysis.

If HDR capture were triggered at the same time as a questionnaire response (or any occupant action), as in the case of Painter *et. al.*'s [2009] study, then the time gap is eliminated completely, without generating excessive data. However, in this study, it was not possible to link the participants' questionnaire responses with those of the cameras, but in future it might be worthy of consideration, for example using a separate user feedback device linked to the HDR camera, as in Konis's study [2014].

#### **10.2.5 Summary**

Despite a number of constraints imposed by the real-world setting, the data collection methodology has largely allowed the research questions to be addressed, and has thus been an effective strategy. The use of multiple methods has been particularly successful, as it has allowed the triangulation of data about the occupants' experience from multiple perspectives. Despite low numbers of participants, the data collected in this mixed method real-world study have provided valuable insights into the experience of occupants as they carried out their daily work tasks in rooms fitted with EC glazing over a period of almost 18 months. As noted by Yan *et. al.* [2015] in their discussion of occupant behaviour models, observed and measured physical data need to be complemented by self-reported data in order to improve model robustness. Thus, while real-world research studies with small sample sizes will not, on their own, be able to provide generalizable findings, they can provide important information, such as contextual factors influencing user acceptance and details of a range of occupant experiences. In this way, this study contributes to the understanding of user experience of and interaction with building systems. A detailed review of the

methodology used in this study within the context of real-world mixed methods research can be found in Painter *et. al.* [2016].

The execution of this data collection highlighted a number of areas that would benefit from further research; these are discussed in the next section.

### **10.3 Recommendations for further research**

#### **10.3.1 Larger user-acceptance study**

The number of data points in this study was limited by the small number of participants, which was itself a function of the opportunistic sample (*i.e.* participants could only be drawn from a total of eight occupants of the two rooms in which the EC windows were installed). A real-world study of the user experience of EC glazing with a larger number of users would be beneficial, since it could provide data for a more diverse range of individuals. It would require the occupants of an entire building, or at least a large glazed area, to take part, which may be logistically challenging. With a larger sample size, the depth of questioning could be reduced, for example with shorter, more frequent questionnaires, and perhaps with one interview at the beginning and end of the data collection. In addition, observed data about occupant interaction with EC window controls (and blinds, if present) should be continuously collected. This kind of study would also provide the opportunity to focus specifically on some of the non-visual aspects linked with the wellbeing of occupants, such as the benefits of having a continuous view through the glazing, provided that blinds were infrequently used.

#### **10.3.2 Further study of the effects of EC glazing tint colour**

Chapter 9 described elements of the data collection that were designed to gather information about the effects of the glazing tint colour on various aspects, including the appearance of the view through the window, the appearance of colours in the room, and several non-visual parameters (alertness, emotional state and perceived pleasantness of the room). It also described two additional



pieces of work that investigated the effect of the glazing on colour discrimination and the daylight spectrum.

The findings suggest that further study of this aspect may be warranted, and helped to highlight a number of practical issues to be considered when designing such a study. A study with a primary focus on the effect of the glazing tint colour, for example, would involve collecting data from participants under specific conditions (*i.e.* when the windows are tinted), and would necessitate that participants respond to questionnaires at times dictated by the researcher. If the study used participants who were working in the space, then this approach would require careful consideration in order to minimise the disruption to participants' work tasks, and the questionnaire would be kept as short as possible. However, given the potential benefits of a larger sample, a study that uses participants invited for short fixed periods of time might be useful. Studies of EC glazing that involve test rooms and invited participants already exist in the literature [Clear *et al.*, 2006; Zinzi, 2006]; however these were not primarily focussed on the effect of glazing colour.

The daylight spectrum work already carried out could be extended so that spectrum measurements are taken simultaneously with participant responses. In this way, it might be possible to quantify how different daylight spectra under different window states affects occupants' perceptions. The exploratory colour discrimination tests suggest that other aspects of colour perception should be assessed, such as colour constancy, colour preference and visual clarity. Tools such as the Macbeth Colour Chart could be considered, in conjunction with the use of three-dimensional coloured objects, giving the opportunity to collect data on texture and detail in addition to colour appearance.

The issue of task illuminance would need to be resolved, given that reductions in window transmittance (*e.g.* for testing under an "all panes tinted" condition) result in a lower illuminance level on the task. Supplementary electric lighting could introduce a confounding factor, since it is the effect of the glazing colour on the daylight in the room that is being investigated. In reality, occupants of rooms fitted with EC glazing will make use of supplementary electric lighting when necessary (or, in a daylight-linked system, this would happen automatically).

However, the use of electric lighting would effectively introduce another variable, since the combination of daylight and electric lighting would result in another spectrum of light. As such, the issue might need to be resolved in another way, *e.g.* by boosting the local light level using a photographer's reflector (but one that does not alter the daylight spectrum).

### **10.3.3 Further HDR study**

Whilst it was difficult to link the HDR-derived data with occupants' experience in this study, the process illustrated the technical and practical challenges of using HDR, and indicated how it could be used in future to assess quantitative luminous conditions in a multi-method study. In order to fully investigate the relationship between HDR-based luminance metrics and the subjective experience of occupants, cameras should be located at or very close to the view position of occupants. This is difficult to achieve in a real-world setting, and it is unlikely that such a set-up could be maintained over a longitudinal period. In these types of studies, a full sized mock-up or computer model of the setting might be necessary to enable view-dependent luminance metrics to be more fully investigated.

In this study, using HDR cameras with a more general view of the room was found to be a source of valuable information, not just about luminance patterns, but also as a record of window states, blind positions and external conditions. A study of EC glazing using HDR should be based in a room in which blinds are rarely used, so that the effect of EC glazing on luminous conditions can be measured more effectively.

### **10.3.4 Anticipation of unstable daylighting conditions**

In Chapter 8, an analysis of daily visual comfort actions and daily façade illuminance conditions indicated that the number of visual comfort actions is related to the amount of variability in façade illuminance, with higher numbers of actions associated with more "spiky" façade illuminance profiles in combination with low solar altitude. The results suggested the potential for a

numerical “solar conditions index” or similar, that could characterise both the spikiness of the illuminance profile and the predominant solar altitude on a given day (*i.e.* altitude when sun is perpendicular to the façade). In this analysis, the spikiness of each profile was obtained by eye, and thus is not a robust enough measure to allow it to be incorporated into a numerical index. In future, a more robust mathematical method could be used to quantify the spikiness of sensor profiles, *e.g.* by calculating the number and frequency of peaks in a profile. This could be automated and applied to large numbers of façade illuminance profiles, and then combined with the sun position. With detailed short-term weather forecasting, it might be possible to calculate an index such as in advance, and the control mode adjusted accordingly to allow better anticipation of challenging conditions.

Clear *et. al.*'s [2006] previously mentioned attempt to quantify the instability of façade illuminance and link it to occupants' experiences highlights the challenge of reducing a complex set of external conditions into one measure or index, and to link it with human behaviour. However, Clear *et. al.*'s study was based on short periods of user exposure to EC windows. The data obtained from the present study, where users' behaviour was monitored continuously over a long-term period, are likely to reflect more consistent behaviour patterns.

### **10.3.5 Optimisation of the control interface for users**

The findings of this study indicate that there are some improvements that could be made to the control interface, such as the addition of an enhanced feedback mechanism. A further study of these issues could be beneficial, since it would allow the exploration and comparison of user experience of other types of control interface (*e.g.* smart-phone or tablet). It could also facilitate the identification of other practical user-interface issues, such as accessibility.

## 10.4 Findings summary

### **Finding 1: EC glazing can provide visual comfort, given certain conditions, the most important of which is seating layout**

The difference in experience between the occupants of the two rooms has highlighted the importance of various aspects, the most important of which is seating layout. Furniture should be arranged so that direct views of the sun are avoided, particularly if other forms of shading are not provided. As the minimum visible transmittance of EC glazing products entering the market decreases, the seating layout may become less critical. However, given the highly subjective nature of visual comfort, it is good practice to avoid seating positions that result in occupants facing windows. In addition, occupants' viewing positions should be made easily adjustable to increase their ability to achieve comfortable conditions. The preferences and sensitivities of individual occupants, and their attitudes towards new technology are also important. These are not within the control of those wishing to implement EC glazing, however, efforts should be made to engage users and ensure that they are given ample instruction about how to use the controls to suit their needs.

### **Finding 2: Glazing should be divided into multiple control zones**

The provision of multiple control zones was generally considered by occupants to be a useful feature. As well as giving more flexible control to users, zoning allowed different settings to be applied to different areas of the glazing. This proved to be of particular importance in the context of how the glazing tint colour affected the perception of colours in the room. Zoning enables a portion of the glazing to be less tinted, thus avoiding the perceptible colour shift that occurs when all glazing is fully tinted. Hence, with the exception of very small areas of glazing, it is recommended that zoning is included.

### **Finding 3: The EC control algorithm's handling of fluctuating external conditions would benefit from improvement**

It was found that visual comfort actions often occurred around times when façade illuminance was in a state of flux, and that the number of visual comfort actions (*i.e.* manual tinting of EC windows or lowering of blinds) was greater on days when the façade illuminance fluctuated. This fluctuation is typical of days on which fast-moving cloud obscures and reveals the sun in quick succession. It was also found that days on which the façade illuminance profile presented many spikes close together appeared to have fewer visual comfort actions, suggesting that if the fluctuation reaches a certain frequency, the resulting effect is similar to that when the façade illuminance is stable, *i.e.* as if the peaks were joined up.

If the system were too sensitive, it would result in rapid cycling of the electrochromic coating. However, in the avoidance of control hysteresis, the system set-up risks not being sensitive enough under these kinds of conditions, when a momentary spike in façade illuminance causes discomfort for an occupant but does not trigger automatic tinting of the glazing. In these situations, a user can, of course, manually tint the glazing. However, the control algorithm could be significantly improved if such conditions could be anticipated by the system, for example using local weather forecasting.

### **Finding 4: Recommendations for future installations**

Several practical issues have arisen from the experience of installing and commissioning EC glazing in this study. A list of recommendations for those wishing to implement the technology, particularly in a retrofit, has been put forward (section 10.1.3). These point to the importance of clear communication between all involved parties in advance of and during the installation, the need for a thorough handover to building owners/occupiers, and the benefit of maintaining a communications link with the manufacturer, so that the control system can be remotely adjusted over a period of months after installation.

### **Finding 5: Suggested improvements for the manual control interface**

The analysis of controls use data indicated that the majority of actions were aimed at fully tinting the lower half of the large window ( $T = 2\%$ ), and that there were relatively few manual overrides targeted an intermediate level of tint ( $T = 6\%$  or  $20\%$ ). This suggests that a simplified control interface could still provide adequate control for users, for example by providing three manual settings instead of four (*i.e.* fully tint, fully un-tint and one intermediate setting).

The user feedback obtained in this study suggests that there may be a case for the provision of remote control, particularly if users need to leave their seats in order to access the manual switches. It is acknowledged that this may not be practical in a shared space with multiple users.

It was noted that manual inputs typically occurred in clusters, consistent with repeated button pressing. This indicates that users might have felt unsure that their input had been registered by the system, particularly since the glazing can take some minutes to visibly change in response to manual inputs. On this basis, it might be useful to include some form of feedback to users incorporated into the control interface, in addition to that already provided (by the movement of the indicator light to show the target of the manual input). This could take the form of a blinking indicator light to reassure users that the system was responding to their input. However, the control interface design should still be as simple as possible in order to be accepted by users.

### **Finding 6: Recommendations for control system refinement to suit the site**

The process of control system refinement in this study was compromised by complex data acquisition arrangements until the control system upgrade some seven months after installation. Hence, adjustments to the control system were made on the basis of feedback from occupants during the initial post-installation period. The final changes were made more than a year after installation, suggesting that a period of at least six months is necessary to allow settings to be refined to suit a range seasonal changes. A summer installation is also recommended, as (among other practical advantages) it allows a settling-in

period to elapse before the advent of low winter sun and the increased likelihood of visual discomfort.

At the outset, it had been expected that control system refinement would rely on data about occupant interaction with the manual controls, as well as feedback from users. It was anticipated that a decrease in the frequency of manual overrides would indicate that the settings were getting closer to optimal for users. However, it was found that a greater number of manual overrides was in fact associated with user satisfaction, and that the users who were least satisfied with the EC glazing preferred to use the blinds for shading and rarely engaged with the manual window controls. Hence, where blinds are available, it is recommended that control system adjustment be made in response to user feedback as well as data about manual controls usage.

**Finding 7: A mixed methods approach is necessary in the study of user acceptance of energy saving retrofit technologies (such as EC glazing)**

The results of this research show that, whilst real-world studies may be subject to practical limitations, a sensitively designed data collection methodology that encompasses self-reported, observed and measured data can increase understanding of the user acceptance of energy saving building technologies such as EC glazing. The integration of different techniques can offset some of the drawbacks of a small study sample and help to reveal additional facets that might have remained hidden if only one technique were used.

## 10.5 Conclusion

The research questions outlined in Chapter 2 have led to a multi-stranded data collection, using data from multiple sources to describe the user experience of EC glazing over a longitudinal period. Using physical measurements in conjunction with data gathered from occupants using self-report and observational techniques, it has also been possible to explore the relationship between physical conditions and user experience. The methods used have been shaped by both the physical constraints of the real-world test-bed and the objectives of the research enquiry.

This study was driven by the overarching research question: “What is the experience of end-users of EC glazing over a long-term period, particularly with regard to visual comfort?” The findings of this research provide a new understanding of the user experience of EC glazing, and thus can inform further technological development and benefit future installations. The results indicate that EC glazing has considerable potential to provide a comfortable environment for occupants, given the right conditions, *i.e.* with appropriate consideration given to furniture layout, intended usage of the space and the needs of individual occupants. The outcomes of this study can enable EC glazing to realise its full potential, both as an energy saving technology and one which brings many benefits to occupants associated with improved daylighting, visual comfort and connection to the outdoors.



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## **Chapter 2**

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## Appendix I

### List of publications

Publication	Details
R. Kelly, J. Mardaljevic, B. Painter, and K. Irvine. The long-term evaluation of electrochromic glazing in an open plan office under normal use: Project outline. In Proceedings of Experiencing Light 2012, Eindhoven, The Netherlands, 2012.	Extended abstract, peer reviewed.
R. Kelly, B. Painter, K. Irvine, and J. Mardaljevic. Capturing the user experience of electrochromic glazing in an open plan office. In Proceedings of the CIE Centenary Conference, Paris, France, 2013.	Extended abstract, peer reviewed.
R. Kelly, B. Painter, J. Mardaljevic, and K. Irvine. Preliminary findings of a case study into the application of electrochromic glazing in a UK office. Proceedings of Lux Europa 2013, 17-19 September, 2013.	Abstract peer reviewed.
R. Kelly, B. Painter, K. Irvine, and J. Mardaljevic. Retrofit electrochromic glazing in an open plan office: A case study. In Proceedings of the International Lighting Conference, Dublin, Ireland, 2013.	Abstract peer reviewed.
J. Mardaljevic, R. Kelly Waskett, B. Painter, and K. Irvine. Retrofit electrochromic glazing in a UK office. SDAR* Journal of Sustainable Design & Applied Research, 2(1):4, 2014.	Full paper peer reviewed.
R. J. Mortimer, D. R. Rosseinsky, and P. M. S. Monk. Electrochromic Materials and Devices. Wiley, 2015. <i>Chapter 19: Electrochromic Glazing in Buildings: A Case Study by John Mardaljevic, Ruth Kelly Waskett, and Birgit Painter.</i>	Edited for publication.
J. Mardaljevic, R. Kelly Waskett, and B. Painter. Neutral daylight illumination with variable transmission glass: Theory and validation. Lighting Research and Technology, 12 2015.	Full paper peer reviewed.
B. Painter, K. Irvine, R. Kelly Waskett, and J. Mardaljevic. Evaluation of a mixed method approach for studying user interaction with novel building control technology. Energies, 2016.	Full paper peer reviewed.

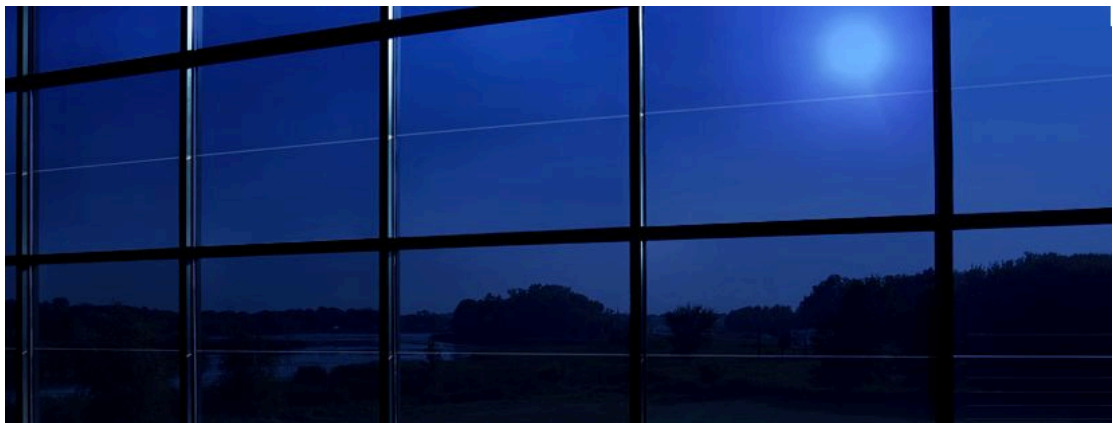
## **Appendix II**

### **Participant information sheet and consent form**



# EC Glazing Project

## Participant Information Sheet



## **What is the aim of the study?**

EC glazing (also known as smart glazing or switchable glazing) is an emerging technology which has the potential to transform the way we use glass in buildings. As part of this project the windows in your office will be upgraded and replaced with new EC windows.

The aim of this research is to find out what effect the EC glazing has on your working environment, looking at aspects such as the lighting conditions, your comfort levels and your experience of the new technology.

## **What is EC glazing and how does it work?**

The full name for EC glass is Electrochromic glass. An EC window is a double glazed window in which one of the panes of glass has a special coating which enables the glass to change its level of tint in response to a small electric current. This means we can switch the glazing to make it lighter or darker to control how much light comes through the window.

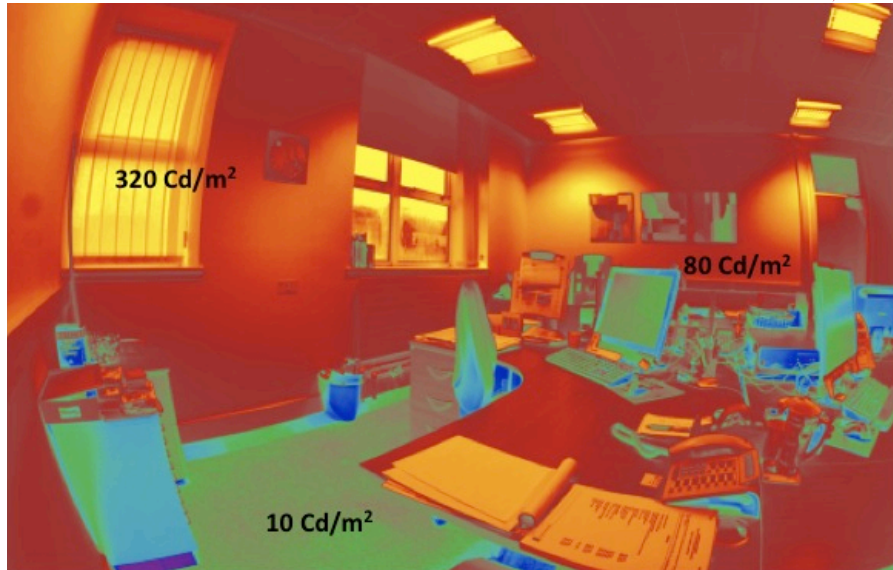
In this project the windows will be controlled automatically, but there will also be a manual control panel available to enable you to override the system to suit your preference. The EC windows we will be using have a blue coloured tint. The depth of colour increases as the window darkens. The windows in your office will be set up to allow the upper, middle (where present) and lower panes of glass to be controlled separately. When the new windows have been installed, you will be given an opportunity to familiarise yourself with the controls and settings.

The product we are using in this study is manufactured in the US by Sage Electrochromics. If you would like to find out more about EC glazing, please visit their website at <http://sageglass.com>.

## **Will you be making other changes to my office?**

Yes. Aside from installing EC windows, we will be making other changes to enable us to get the information we need from the research:

1. Before the new windows are installed, some upgrading work will be carried out on the lighting system currently installed in your office. This will include the provision of a new control system, which will automatically dim the lights up or down depending on how much daylight is entering through the windows. Systems like this are routinely installed in modern offices, as they can be very effective at reducing energy bills. The system will have a manual override control to enable you to change the dimming level set by the system at any time. When the new lighting system is installed, you will be given an opportunity to ask questions and familiarise yourself with the controls.
2. We will be installing a small number of digital cameras, which will be mounted in your office for the duration of the project. These will be set up to automatically record images of your office at intervals throughout each day. These are called High Dynamic Range (HDR) images, and capture information about the lighting conditions in the room. An example of a HDR capture is shown in below. The HDR captures will be stored automatically in a database on a computer, where they will be analysed by specialist software. These images will not be used for any purpose other than that of this research project, and will not be viewed by anyone outside of the research team.



*An example of a HDR capture*

3. We will be installing other pieces of small equipment and wiring to monitor items such as the lighting control system, the EC window controller and the air conditioning unit. We will also install a temperature sensor or sensors somewhere in the room. We will also monitor the use of window blinds where applicable, either remotely or by direct observations made during visits to your office.

In all instances we will endeavour to ensure that these pieces of equipment and their operation will not interfere with your ability to carry out your work as normal.

### **What does participation involve?**

During the study we would like to collect information about the current lighting conditions in your work place and the effect of the EC windows after they have been installed. This will be done using a combination of:

- Interviews with you, in which you will be asked how you feel about the lighting conditions, your comfort levels and your experience of the work environment in the office. These will be carried out at key stages throughout the project.
- Questionnaires in which you will be asked about the lighting conditions, comfort levels and your experience of the work environment. These will be carried out at regular intervals throughout the project.
- Paper or electronic diaries in which you can give feedback at any time about your experience of the new technology in your workplace.

At the start of the project, we would like you to complete a background questionnaire in which you will be asked to give relevant background information about yourself, including age, gender, eyesight, and your general feelings about lighting conditions and your comfort at work. All data will be collected in the strictest confidence – please see below for more information on this.

## How will data be collected?

Your responses to the questionnaires will be recorded through written or electronic material. Interviews will be recorded using hand-written notes and/or voice recording equipment. Diary entries will be recorded through written or electronic material. Other measurements, including the HDR images, will be logged remotely via a computer.

## Will my taking part in the study be kept confidential?

All data collected and processed in this study will be handled in compliance with the Data Protection Act 1998. All your details will be kept confidential with access restricted to researchers directly involved in the project (see Contacts). Where data may be complementary to other or future projects; all data will be anonymised. You will remain anonymous in any material disseminated from the study (for example, a report or journal article), so your name or other personal details will not appear in any material (written, oral or otherwise) arising from this study.

## Can I withdraw from the study?

Participation in this project is voluntary. You are free to withdraw from the study at any time. Participation in the study also requires your formal consent (please see attached consent form).

You are encouraged to contact the research team with any concerns regarding the study at any stage throughout the project. If you choose to withdraw from this study, you can inform a member of the research team using the contact details below.

## Contacts

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If you have any general questions about your rights as a participant, or wish to make a complaint, you can contact De Montfort University's Ethics Administrator Professor Bernd Stahl, on 0116 207 8252, or email [bstahl@dmu.ac.uk](mailto:bstahl@dmu.ac.uk).

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# Appendix III

## Preliminary interview form

### Section 1: What makes a pleasant office environment?

For each of the following items, please indicate how important you think they are in making a pleasant office environment.

	Unimportant				Very important
	1	2	3	4	5

1.1 Good temperature control

Notes

1.2 Good lighting

Notes

	Unimportant				Very important
	1	2	3	4	5

1.3 Windows

Notes

1.4 A view

Notes

	Unimportant				Very important
	1	2	3	4	5

1.5 Comfortable furniture

Notes

1.6 Privacy

Notes

		<b>Unimportant</b>				<b>Very important</b>
		<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>

1.7 No noise

*Notes*

1.8 Controllable lighting

*Notes*

		<b>Unimportant</b>				<b>Very important</b>
		<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>

1.9 Controllable windows/blinds

*Notes*

1.10 An attractive interior

*Notes*

		<b>Unimportant</b>				<b>Very important</b>
		<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>

1.11 A good computer monitor

*Notes*

1.12 Other

*Please specify*

## Section 2: Your sensitivity to environmental conditions

Please indicate how sensitive you are to each of the following items, with reference to your office environment.

		Not sensitive				Very sensitive
		1	2	3	4	5

2.1 Glare

Notes

2.2 Cold

Notes

		Not sensitive				Very sensitive
		1	2	3	4	5

2.3 Heat

Notes

2.4 Gloominess

Notes

2.5 Noise

Notes

		Not sensitive				Very sensitive
		1	2	3	4	5

2.6 Visual distraction

Notes

2.7 When you are working, what is your preferred light level in your workspace?

Very low	Low	Moderate	Bright	Very bright
----------	-----	----------	--------	-------------

Notes



### Section 3: You and your office

In your office, in general:

**3.1 Overall, how satisfied are you with your office?**

Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied
-------------------	--------------	---------------------------------------	-----------	----------------

Notes

**3.2 How satisfied are you with your ability to control the light level in your room?**

Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied
-------------------	--------------	---------------------------------------	-----------	----------------

Notes

**3.3 How satisfied are you with your ability to control the heating in your room?**

Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied
-------------------	--------------	---------------------------------------	-----------	----------------

Notes

**3.4 How satisfied are you with your ability to control the air conditioning in your room?**

Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied
-------------------	--------------	---------------------------------------	-----------	----------------

Notes

**3.5 How do you find the level of daylight in the room?**

Too dark	Dark	Just right	Bright	Too bright
----------	------	------------	--------	------------

Notes

**3.6 How do you find the level of electric lighting in the room?**

Too dark	Dark	Just right	Bright	Too bright
----------	------	------------	--------	------------

Notes

**3.7 How do you find the temperature in the room?**

Too cold	Cold	Just right	Warm	Too warm
----------	------	------------	------	----------

Notes

**3.8 Do you experience glare from the windows?**

Never Rarely Sometimes Often All the time

Notes

**3.9 Do you experience glare from the ceiling lights?**

Never Rarely Sometimes Often All the time

Notes

**3.10 Do you experience reflections on your computer screen?**

Never Rarely Sometimes Often All the time

☐ ☐ ☐ ☐ ☐

Notes

**3.10a If applicable, please indicate the most common source of these reflections:**

*Please tick one only*

- ☐ Windows
- ☐ Ceiling lights
- ☐ Bright patch of wall

☐ Other  
*Please specify*

**3.11 How often do you adjust the window blinds?**

Never Rarely Sometimes Often

☐ ☐ ☐ ☐

Notes

**3.11a If applicable, please indicate the most common reason for adjusting your blinds:**

*Please tick one only*

Reasons for lowering/closing

- ☐ Glare from sky
- ☐ Glare from sunlight
- ☐ Reflections on computer screen

Overheating

Privacy

Other  
*Please specify*

Reasons for raising/opening

To increase daylight

To see out

Other  
*Please specify*

**3.12 In terms of how your room is lit during daylight hours, do you think that the room is:**

*Please tick one only*

Predominantly lit by the ceiling lights

*Notes*

Lit by a combination of ceiling lights and daylight from windows

Predominantly lit by daylight from the windows

**3.13 How do you find the noise levels in your room?**

Too noisy

Noisy

Just right

Quiet

Too quiet

*Notes*

Section 4: About You

The following questions are about you. Your answers are for analysis purposes only. No names or other personal details about you will appear in any material arising from the research.

4.1 What are your typical working hours per day?      Less than 8 hrs      8 - 10 hrs      Over 10 hrs

4.2 Do you wear glasses or contact lenses?      Yes      No

4.2a If yes, how often do you wear them?      All the time  
During specific tasks

Other  
Please specify

4.3 Are you visually impaired?      Yes      No      Don't know

4.3a If yes, please specify

4.4 Are you colour blind?      Yes      No      Don't know

Notes

4.5 Do you currently have any health issues that affect your comfort at work?      Yes      No

4.5a If yes, please briefly explain how this affects your comfort at work:

4.6 Age range      Under 20      20-29      30-39      40-49      50-59      60 or over

4.7 Gender      M      F

## Appendix IV

### Preliminary interview results

#### Responses to “What makes a pleasant office environment?”

1 = Unimportant, 5 = Very important

Item	A1	B1	B2	B3
Good temperature control	5	5	5	5
Good lighting	5	5	5	4
Windows	5	5	4	4
A view	5	2	4	3
Comfortable furniture	5	5	4	5
Privacy	5	3	5	2
No noise	5	4	2	1
Controllable lighting	5	4	4	4
Controllable windows/blinds	5	4	4	5
An attractive interior	5	4	5	4
A good computer monitor	5	5	5	4
Other	3 (Social)	3 (Music)	3 (Social)	N/A

**Responses to “Please indicate how sensitive you are to each of the following items, with reference to your office environment.”**

**Preferred light level: 1 = Very low, 5 = Very bright**

**All other items: 1 = Not sensitive, 5 = Very sensitive**

<b>Item</b>	<b>A1</b>	<b>B1</b>	<b>B2</b>	<b>B3</b>
Glare	5	3	5	4
Cold	4	3	1	3
Heat	2	2	5	3
Gloominess	5	4	2	3
Noise	5	4	5	2
Visual distraction	4	3	1	2
Preferred light level	3	3	2	3

**Responses to “In your current office, how satisfied are you with...?”**

**Overall satisfaction:** 1 = Very dissatisfied, 5 = Very satisfied

**Light level:** 1 = Too dark, 5 = Too bright

**Temperature:** 1 = Too cold, 5 = Too warm

**Frequency of glare & reflections:** 1 = Never, 5 = All the time

**Perceived noise level:** 1 = Too noisy, 5 = Too quiet

Item	A1	B1	B2	B3
Overall satisfaction	3	4	3	3
<i>Satisfaction</i>				
Ability to control light level	4	4	3	2
<i>Satisfaction</i>				
Ability to control heating	1	4	3	4
<i>Satisfaction</i>				
Ability to control air conditioning	4	4	2	2
<i>Satisfaction</i>				
Level of daylight	3	3	2	3
<i>Perceived light level</i>				
Level of electric light	3	3	5	3
<i>Perceived light level</i>				
Temperature	3	4	5	5
<i>Perceived temperature</i>				
Glare from windows	5	3	4	4
<i>Frequency</i>				
Glare from ceiling lights	1	1	3	1
<i>Frequency</i>				
Reflections on computer screen	3	3	2	3
<i>Frequency</i>				
Noise	2	3	3	3
<i>Perceived noise level</i>				

## **Appendix V**

### **Questionnaire**



## EC Glazing Study Online Questionnaire

*Please complete this questionnaire at your desk during daylight hours.  
It is important that you complete the questionnaire in one sitting.*



### 1. Please enter your participant ID number

### 2. Please indicate your room number.

☐ Room 0.29

☐ Room 0.30

The next four questions are about the lighting conditions in your office. For each question, please consider the conditions as they are at this precise moment.

### 3. How would you describe the total light level (from the windows and overhead lighting together) in your office at the moment?

☐ 1 Too dark

☐ 2

☐ 3 Just right

☐ 4

☐ 5 Too bright

Additional comments

### 4. How would you describe the distribution of light in your office at the moment?

☐ 1 Poorly distributed

☐ 2

☐ 3

☐ 4

☐ 5 Nicely distributed

Additional comments

### 5. At the moment, do you think the room is:

☐ Predominantly lit by the ceiling lights

☐ Lit by a combination of ceiling lights and daylight from the windows

☐ Predominantly lit by daylight from the windows

Additional comments

**6. How would you describe the level of daylight in your office at the moment?**

- ☐ 1 Too little daylight
- ☐ 2
- ☐ 3 Just right
- ☐ 4
- ☐ 5 Too much daylight

Additional comments

The next set of questions are about your visual comfort, i.e. your experience of glare and reflections on your computer screen.  
Please consider your response in terms of your experience at this precise moment.

**7. At the moment, are you experiencing any reflections on your computer screen?**

- ☐ Yes
- ☐ No

If a yes response is given to Q7, the following question appears:

**8. What do you think is the source of the reflections?**

- ☐ 1 Windows
- ☐ 2 Ceiling lights
- ☐ 3 Bright patch of wall
- ☐ 4 Other (please specify)

**9. At the moment, are you experiencing glare caused by light shining directly into your eyes?**

- ☐ Yes
- ☐ No

If a yes response is given to Q9, the following two questions appear:

**10. What do you think is the source of the glare?**

- ☐ 1 Windows
- ☐ 2 Ceiling lights
- ☐ 3 Bright patch of wall
- ☐ 4 Other (please specify)

**11. How would you describe the level of glare?**

1 Noticeable

2 Acceptable

3 Uncomfortable

4 Intolerable

☐

☐

☐

☐

Additional comments

The following two questions are about how you feel at the moment. Please consider your response in terms of how you feel right now.

12. Using the scale below, please indicate how alert or tired you currently feel.

- ☐ 1 Extremely alert
- ☐ 2
- ☐ 3 Alert
- ☐ 4
- ☐ 5 Neither alert nor sleepy
- ☐ 6
- ☐ 7 Sleepy, but no difficulty staying awake
- ☐ 8
- ☐ 9 Extremely sleepy

Additional comments

13. Overall, how would you describe your emotional state at the moment?

1 Very poor	2 Poor	3 Average	4 Good	5 Excellent
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Additional comments

The next two questions are about the clarity of the view through your window. As with previous questions, please consider your response in terms of how conditions are at this precise moment.

14. How satisfied are you with the clarity of the view through the windows at the moment?

- ☐ 1 Very dissatisfied
- ☐ 2
- ☐ 3 Neither satisfied nor dissatisfied
- ☐ 4
- ☐ 5 Very satisfied

Additional comments

**15. At this moment, how easy is it to gauge the weather outside by looking through the window?**

- ☐ 1 Very difficult
- ☐ 2
- ☐ 3 Neither difficult nor easy
- ☐ 4
- ☐ 5 Very easy

Additional comments

The next two questions are about the temperature in your office. As with previous questions, please consider your response in terms of how conditions are at this precise moment.

**16. How would you describe the temperature in your office at the moment?**

- ☐ 1 Too cold
- ☐ 2
- ☐ 3 Just right
- ☐ 4
- ☐ 5 Too hot

Additional comments

**17. If the sun is coming into your room at the moment, please indicate whether the heat of the sun is causing discomfort for you. If there is no sun coming in, please choose N/A.**

- ☐ 0 N/A
- ☐ 1 Very uncomfortable
- ☐ 2
- ☐ 3 Neither comfortable nor uncomfortable
- ☐ 4
- ☐ 5 Very comfortable

Additional comments

The final three questions are about your general impressions. Note that the final question is different from the all the other questions in that it asks you to consider conditions over the past two weeks.

18. Using the scale below, please indicate how pleasant you find your office at the moment.

- ☐ 1 Very unpleasant
- ☐ 2
- ☐ 3 Neither pleasant nor unpleasant
- ☐ 4
- ☐ 5 Very pleasant

Additional comments

19. Please use the scales below to describe the appearance of colours in your office at the moment.

	1 Not at all	2 A little	3 Moderately	4 Quite	5 Very much so
Natural	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Vibrant	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Additional comments

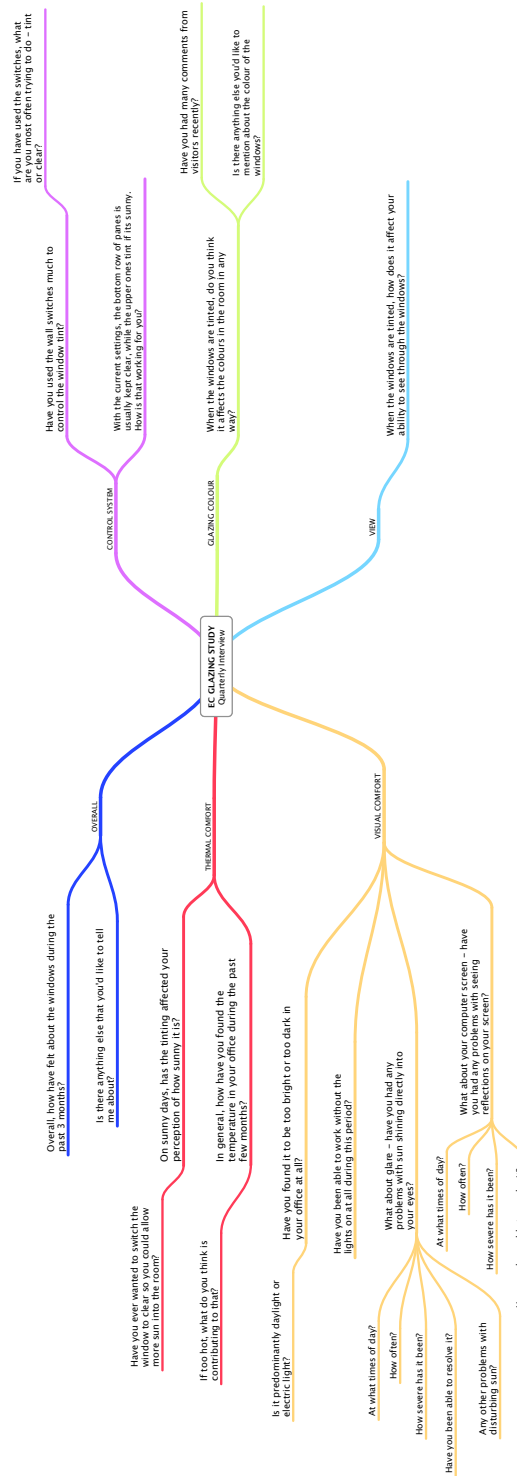
20. During the past two weeks, please indicate to what extent your work was hindered by direct sunlight in your office using the scales below.

	1 Not at all	2 A little	3 Moderately	4 Quite a lot	5 Very much
Heat of the sun	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Direct sunlight on your desk	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reflections on your screen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Additional comments

# Appendix VI

## Interview questions MindMap

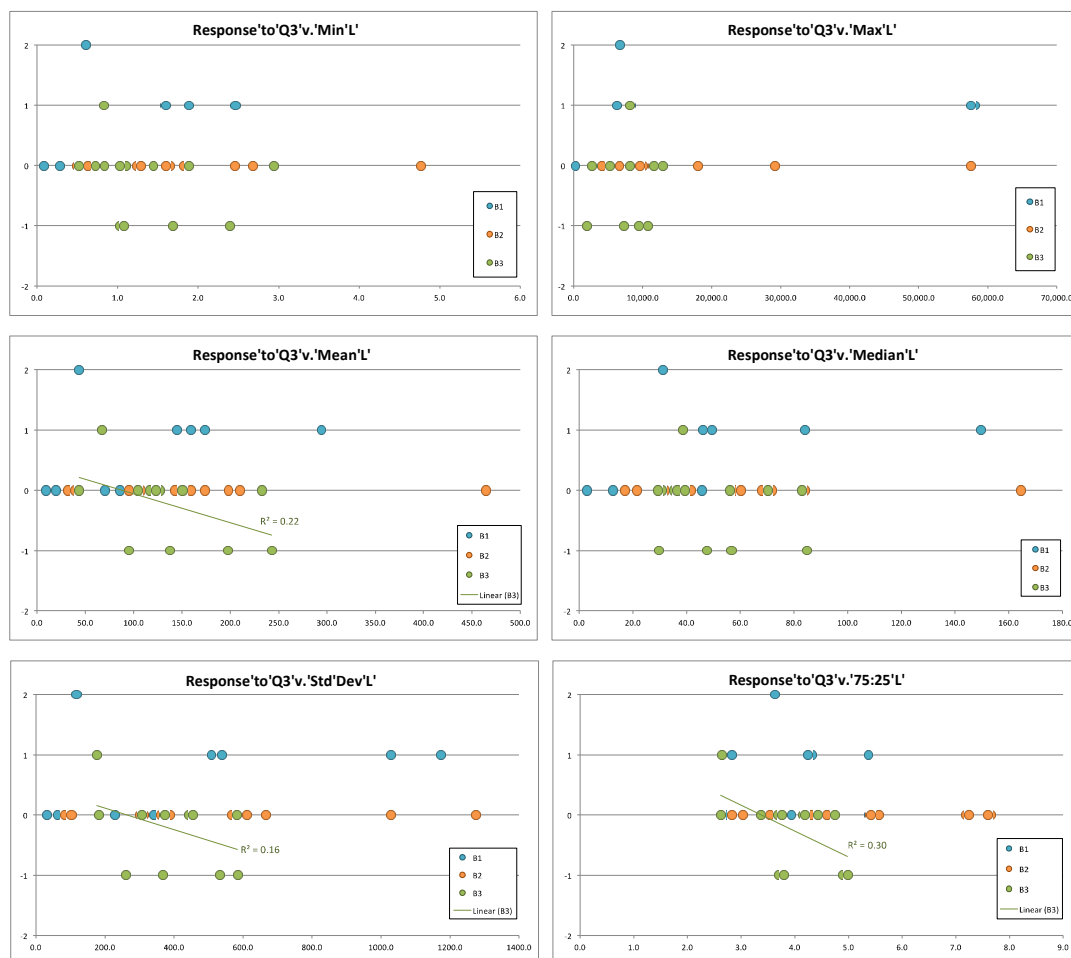


## Appendix VII

### HDR metrics plotted against responses to Q3 - 6

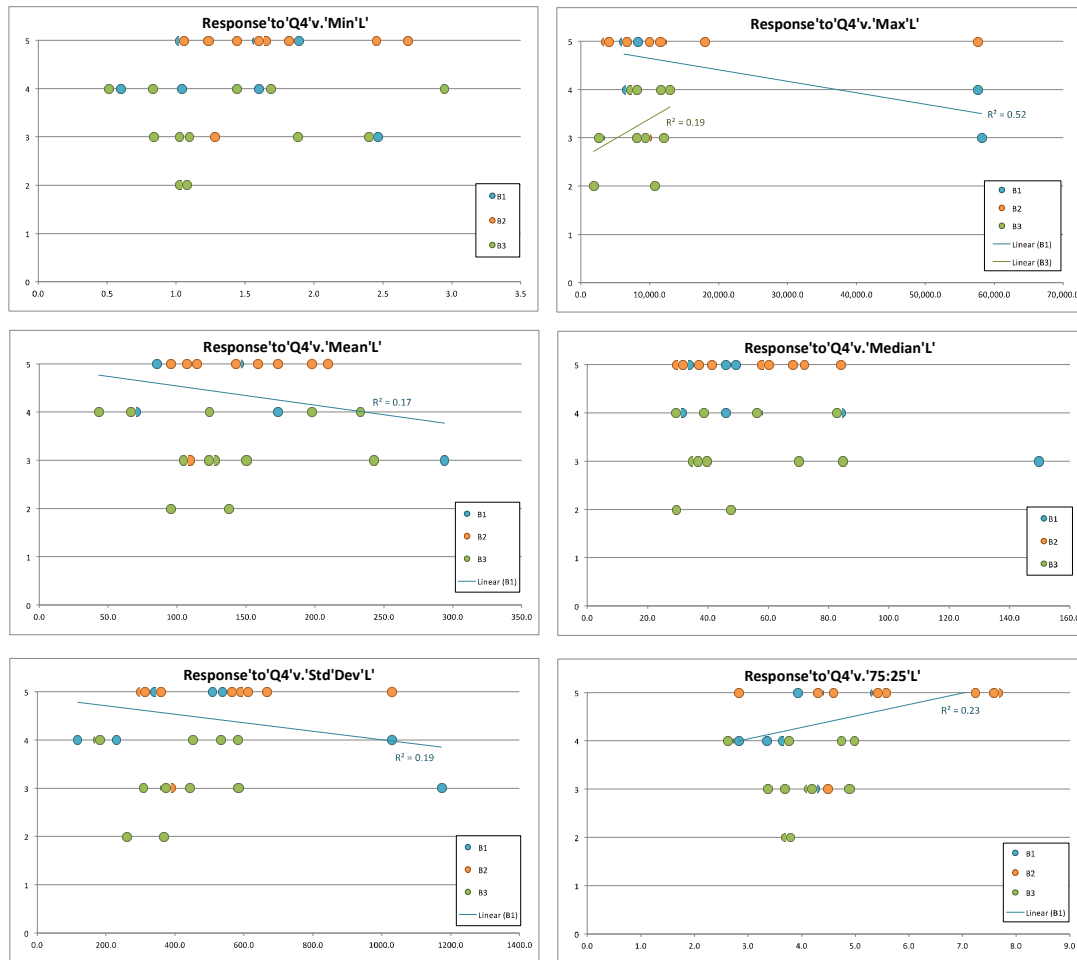
*Perceived light level (Q3) v. luminance metrics*

2 = Too bright, 0 = Just right, -2 = Too dark



## Perceived distribution of light (Q4) v. luminance metrics

1 = Poorly distributed and 5 = Nicely distributed

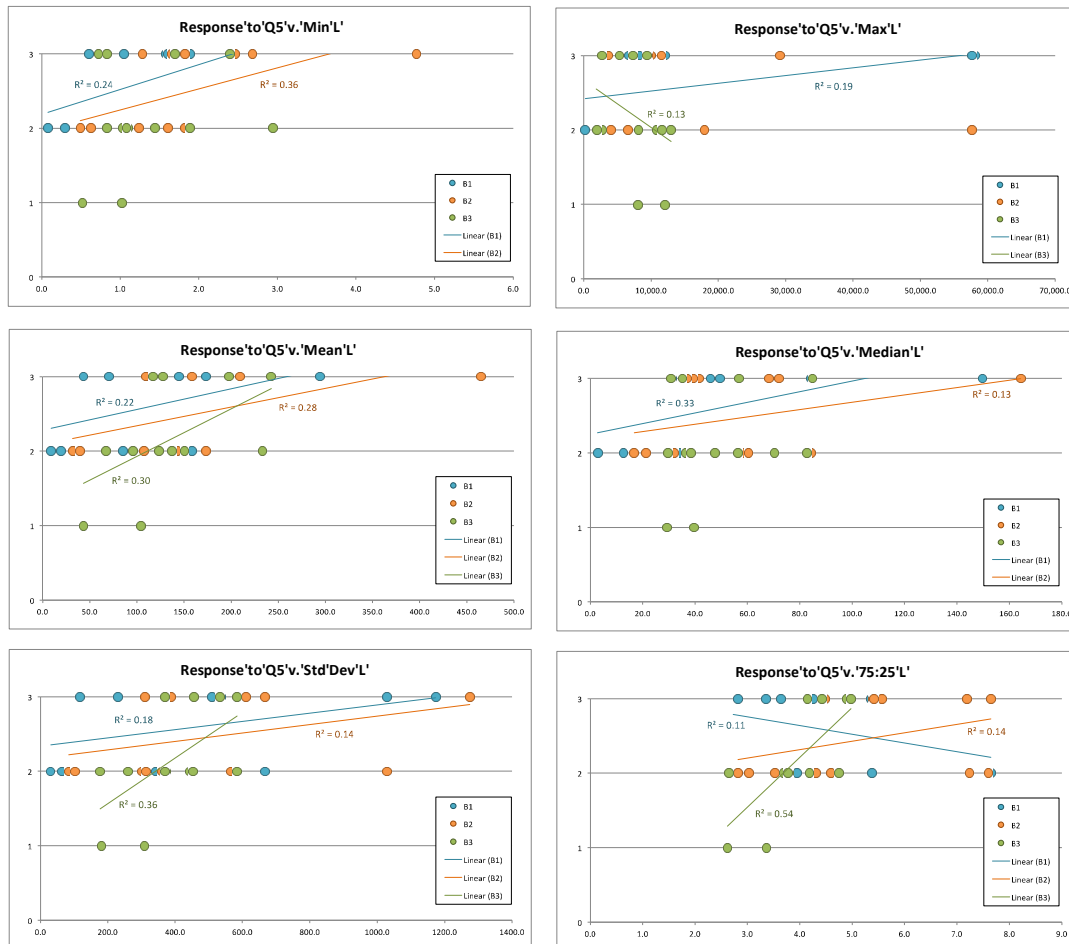




## Perceived dominance of daylight (Q5) v. luminance metrics

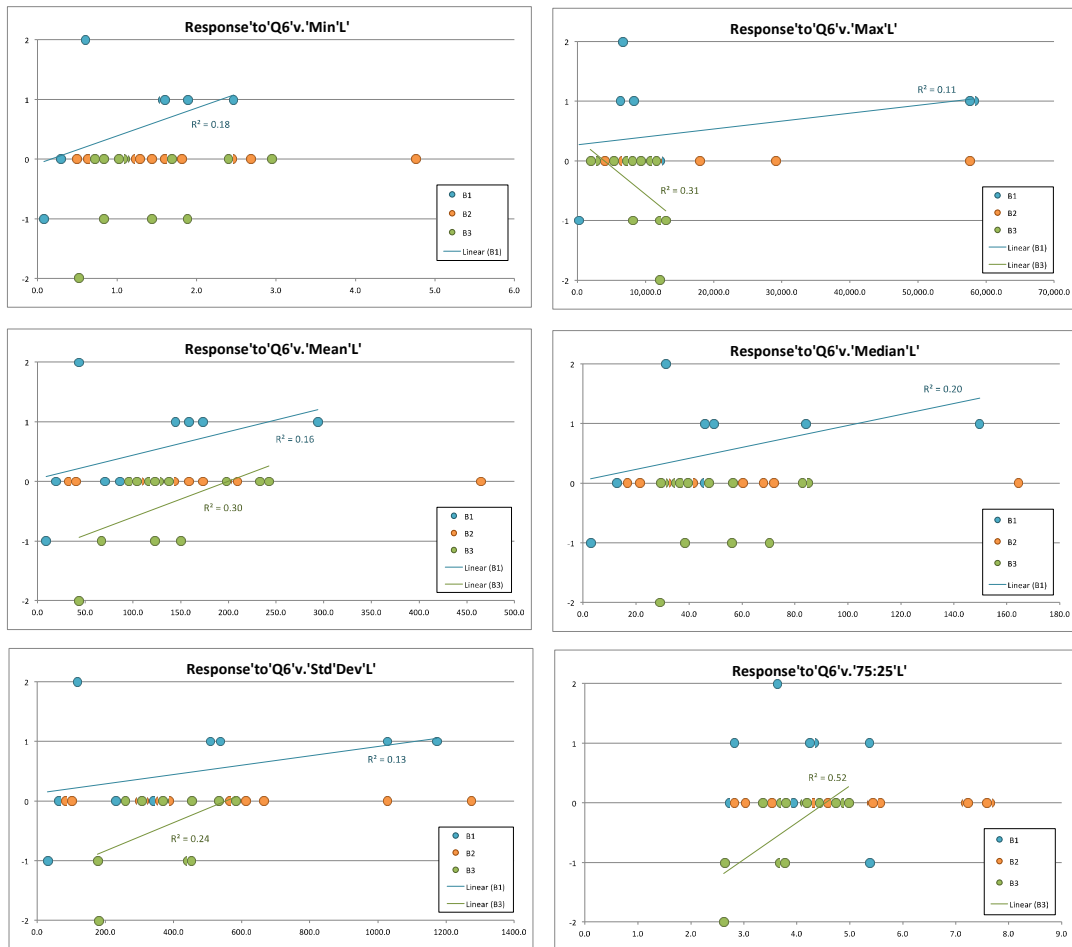
1 = Predominantly electric light, 2 = Combination of electric and daylight,

3 = Predominantly daylight



## Perceived quantity of daylight (Q6) v. luminance metrics

2 = Too much daylight, 0 = Just right, -2 = Too little daylight



## Appendix VIII

### Façade photo analysis

#### *Room A*

Total = 6 panes

Number of panes covered	Occlusion
0	0%
1	17%
2	33%
3	50%
4	66%
5	83%
6	100%

#### *Room B*

Total = 8 panes

Number of panes covered	Occlusion
0	0%
1	13%
2	25%
3	38%
4	50%
5	63%
6	75%
7	88%
8	100%

Where a blind is covering a fraction of a pane or panes, then the occlusion will be somewhere between the whole pane percentages listed above. For example, if 5.5 panes are covered in room B, then % occlusion will be  $(5.5/8) \times 100 = 69\%$ .

### **Façade photos**

Total number = 42

Images where blind position is indeterminate = 9

Remainder used in analysis = 33



131205 15:00

Room A: 0%

Room B: 25%



131206 11:51

Room A: 0%

Room B: 68%



131209 10:50

Room A: No info

Room B: No info



131210 10:00

Room A: 0%

Room B: 20%



131210 16:00

Room A: 0%

Room B: 20%



131211 09:48

Room A: 0%

Room B: 20%



131211 14:08

Room A: 0%

Room B: 50%



131214 14:13

Room A: 0%

Room B: 25%



131218 08:45

Room A: No info

Room B: No info



131218 14:08

Room A: 0%

Room B: 38%



140108 09:50

Room A: No info

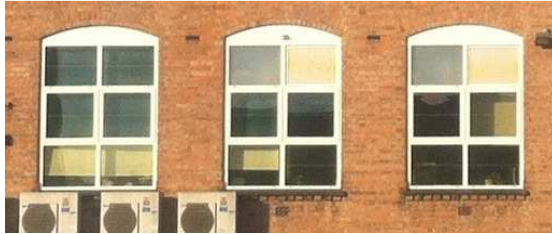
Room B: No info



140116 09:53

Room A: No info

Room B: No info



140116 13:36

Room A: 33%

Room B: 90%



140122 16:05

Room A: 33%

Room B: 44%



140123 12:32

Room A: 33%

Room B: 85%



140129 09:48

Room A: 33%

Room B: 60%



140129 15:10

Room A: 33%

Room B: 60%



140205 09:53

Room A: 0%

Room B: 65%





140205 16:08

Room A: 0%

Room B: 55%



140211 12:50

Room A: 0%

Room B: 75%



140212 09:44

Room A: 15%

Room B: 44%



140212 16:09

Room A: 15%

Room B: 44%



140226 09:40

Room A: No info

Room B: No info



140226 13:23

Room A: 0%

Room B: 56%



140304 09:45

Room A: No info

Room B: No info



140304 16:06

Room A: 0%

Room B: 38%



140312 11:02

Room A: 33%

Room B: 38%



140325 10:10

Room A: 0%

Room B: 38%



140325 16:09

Room A: 0%

Room B: 38%



140402 12:47

Room A: 0%

Room B: 38%



140402 17:37

Room A: 0%

Room B: 38%



140409 09:53

Room A: No info

Room B: No info





140417 09:02

Room A: No info

Room B: No info



140417 15:31

Room A: 0%

Room B: 38%



140422 09:04

Room A: 0%

Room B: 38%



140429 11:42

Room A: 0%

Room B: 25%



140430 10:23

Room A: 0%

Room B: 25%



140507 12:02

Room A: 0%

Room B: 25%



140521 09:40

Room A: No info

Room B: No info



140521 15:37

Room A: 0%

Room B: 60%



140603 09:37

Room A: 0%

Room B: 60%



140618 09:57

Room A: 0%

Room B: 60%

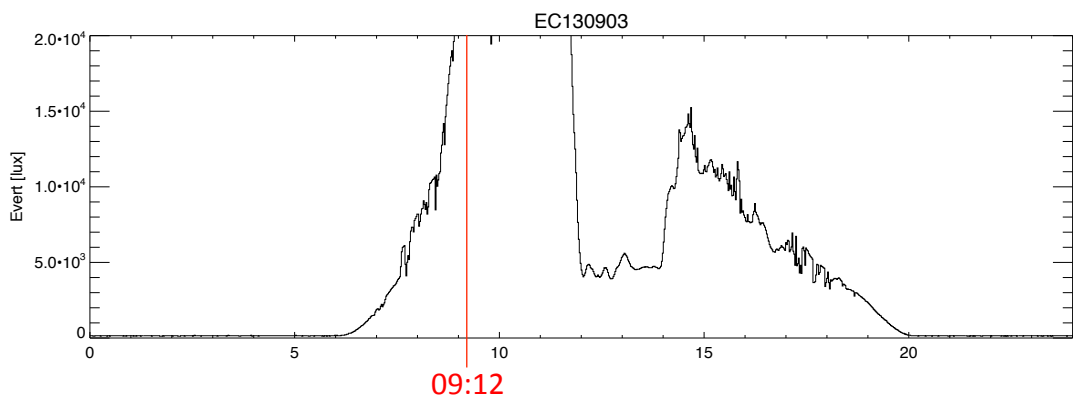
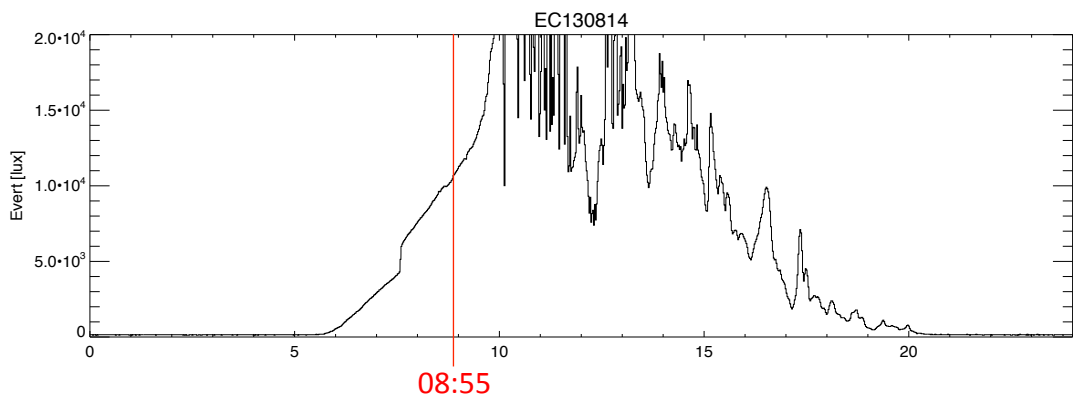
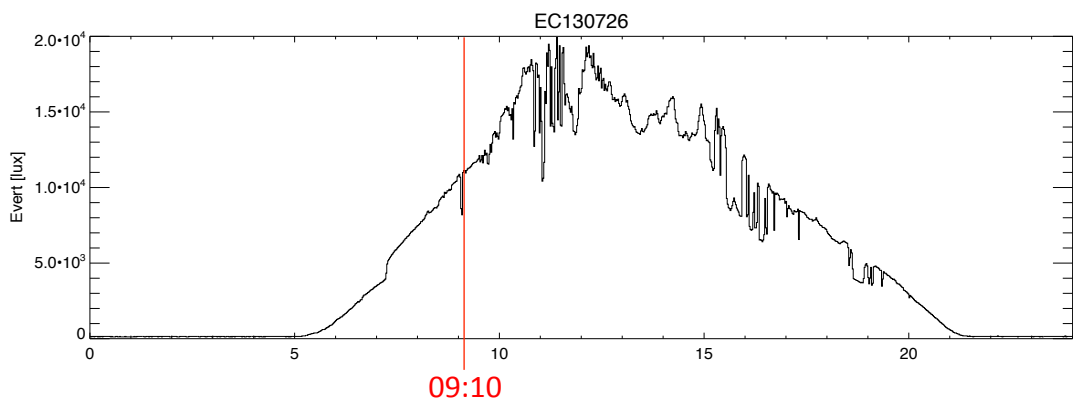
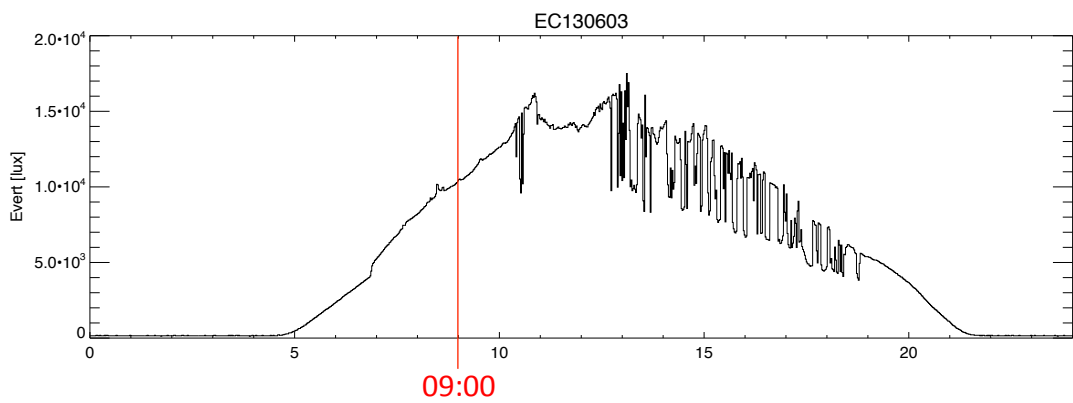
Average blind occlusion for room A = 7%

Average blind occlusion for room B = 46%

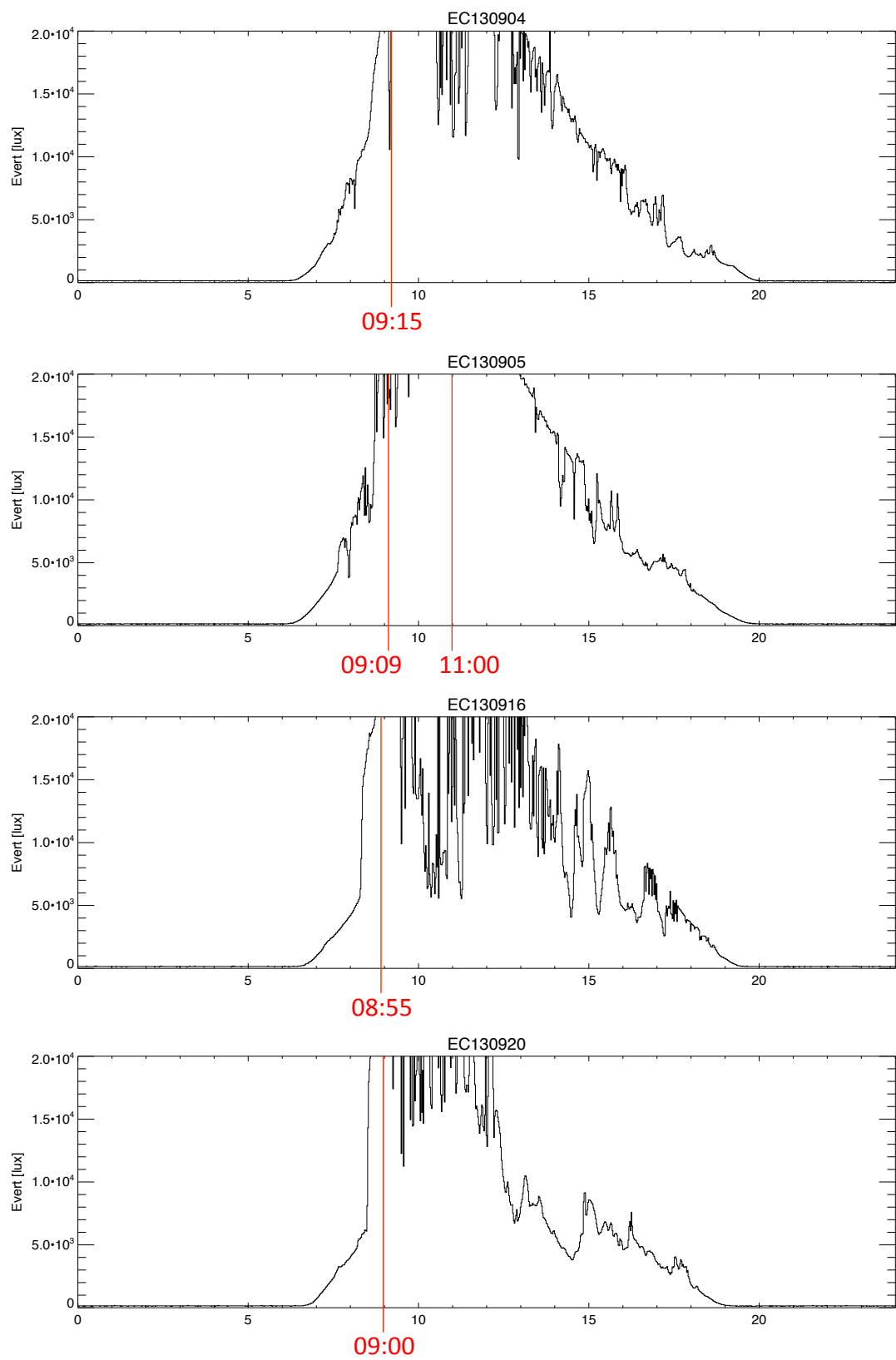
## **Appendix IX**

### **Façade sensor analysis for the “no change in %T” cases**

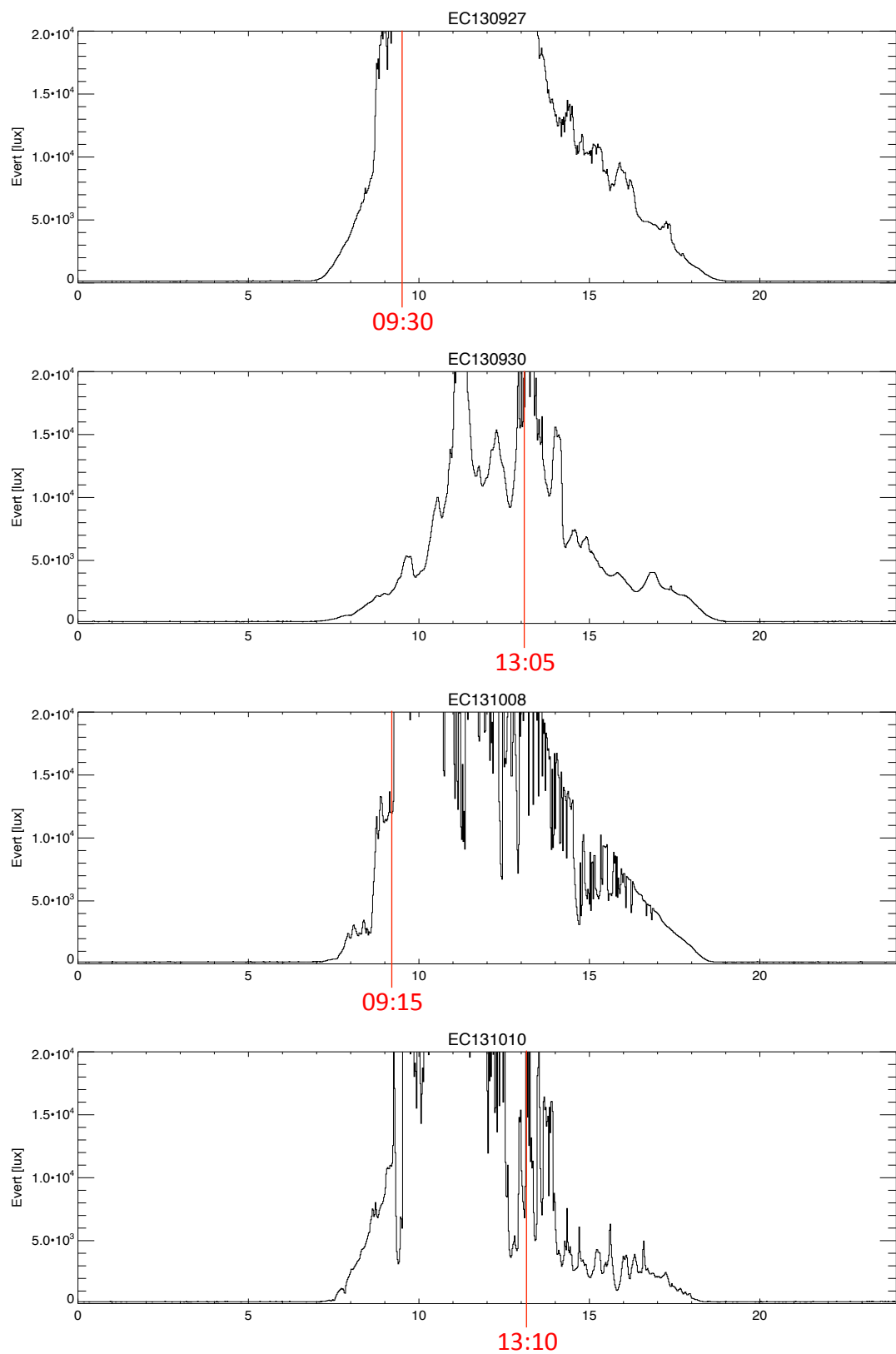
“No change in %T” cases



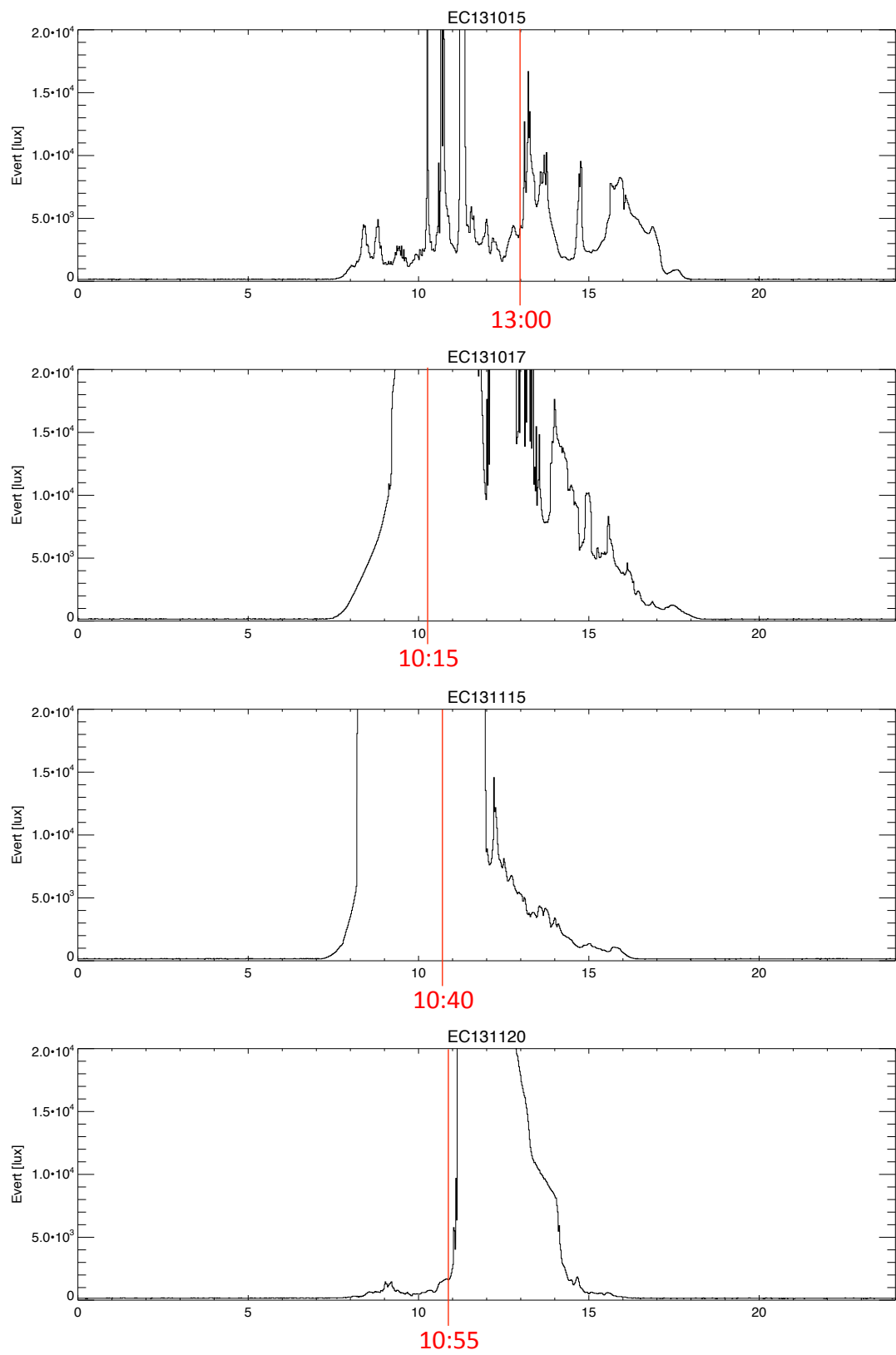
“No change in %T” cases



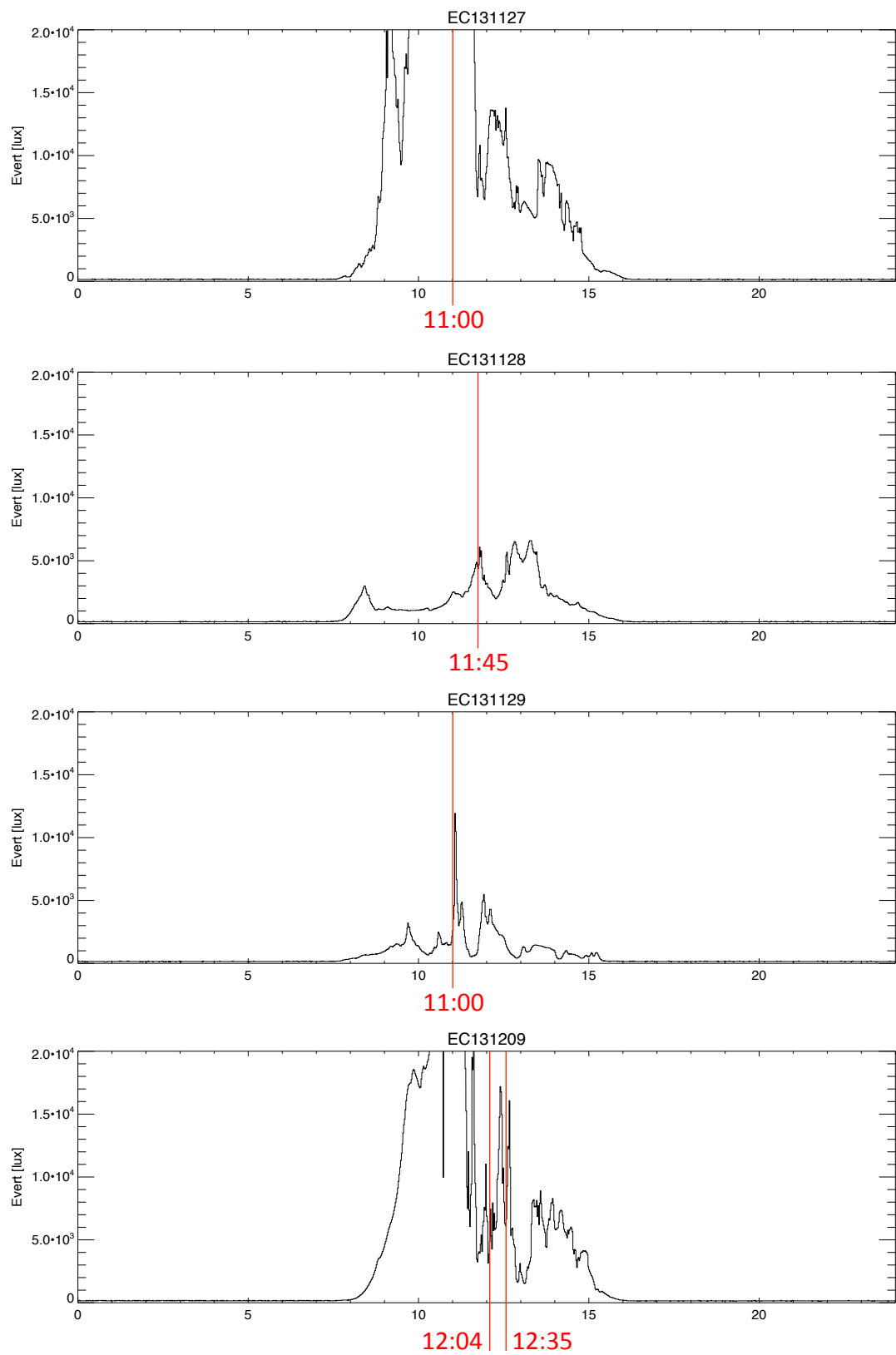
“No change in %T” cases



“No change in %T” cases

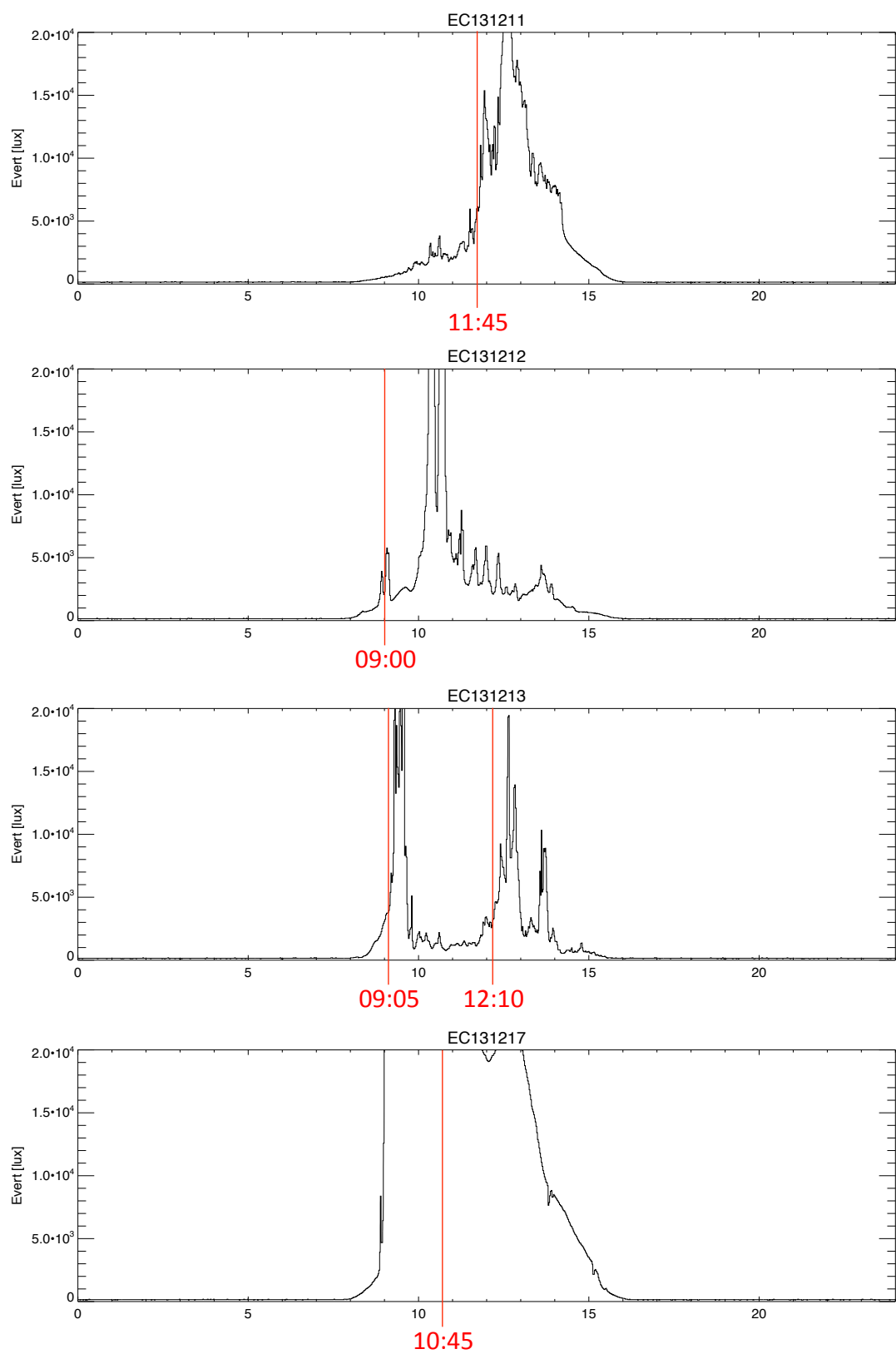


“No change in %T” cases

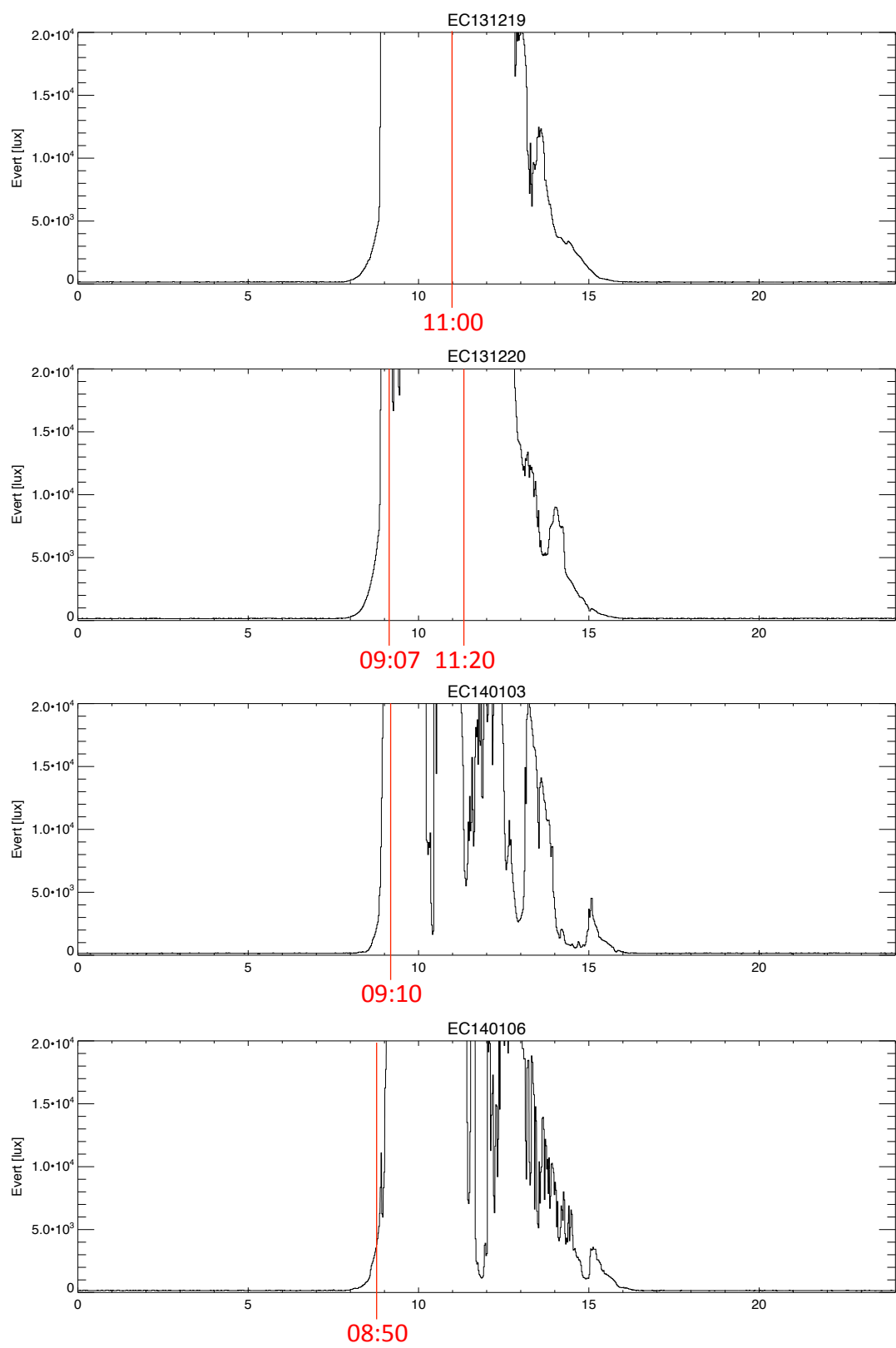




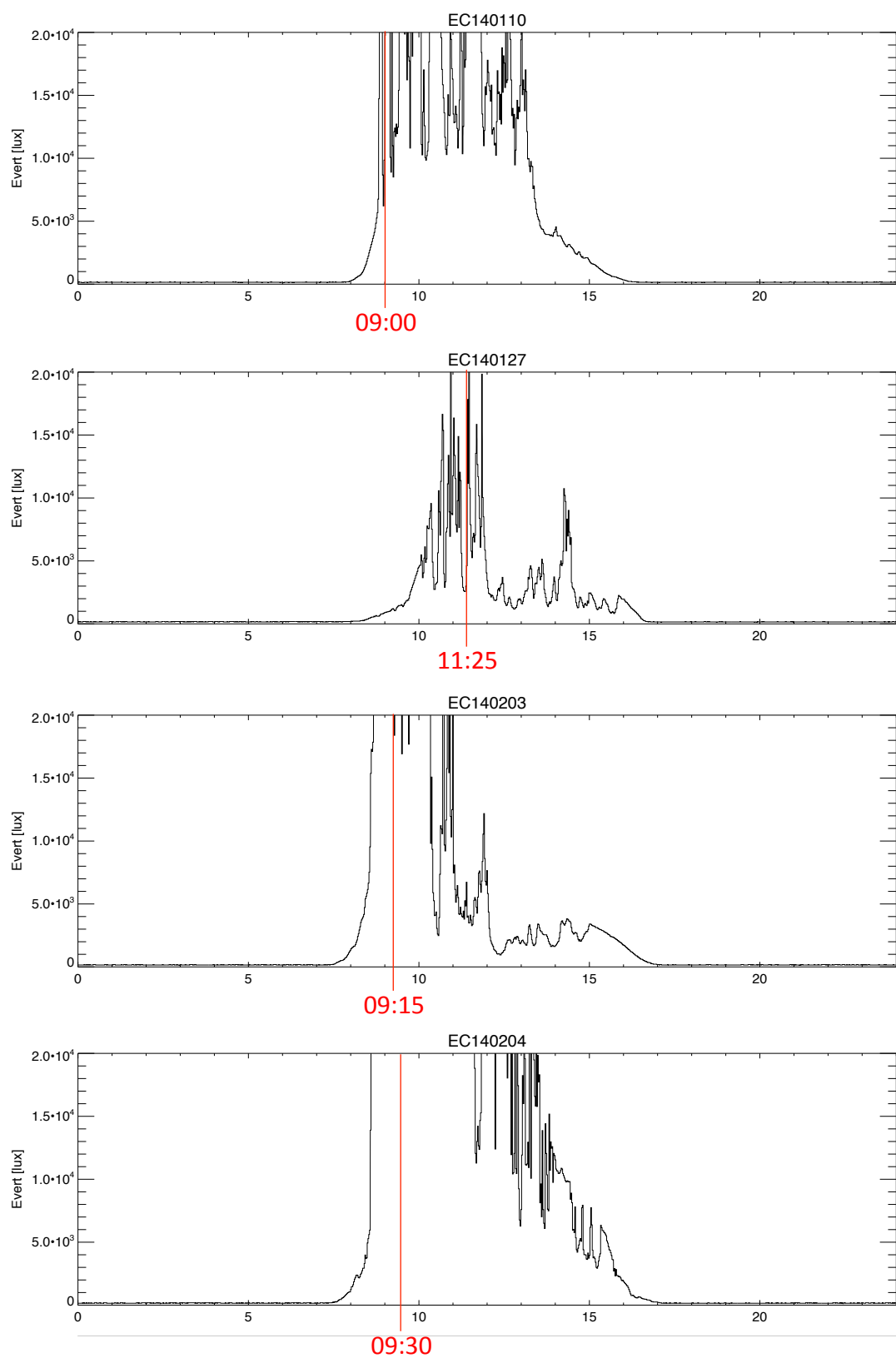
“No change in %T” cases



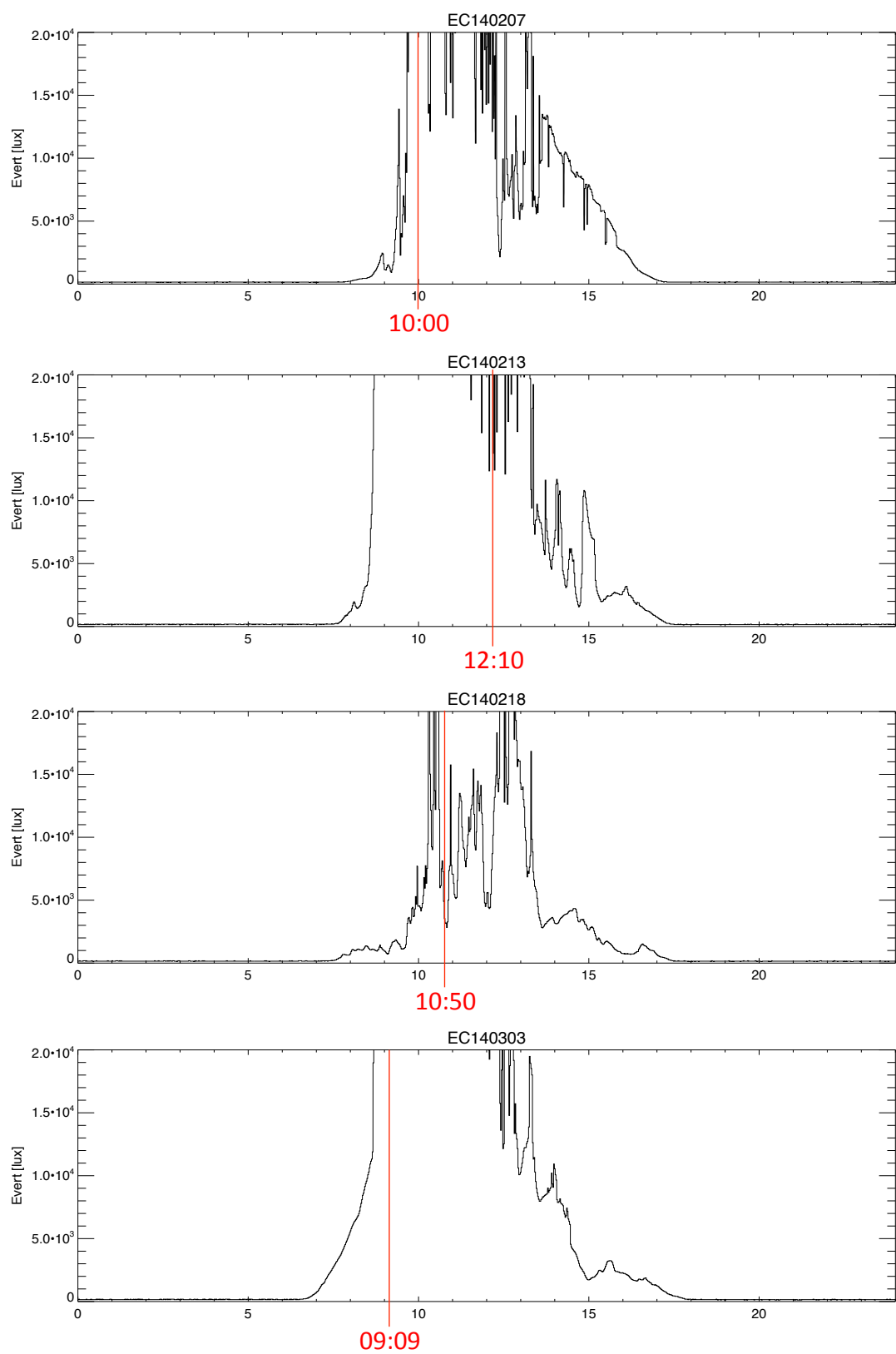
“No change in %T” cases



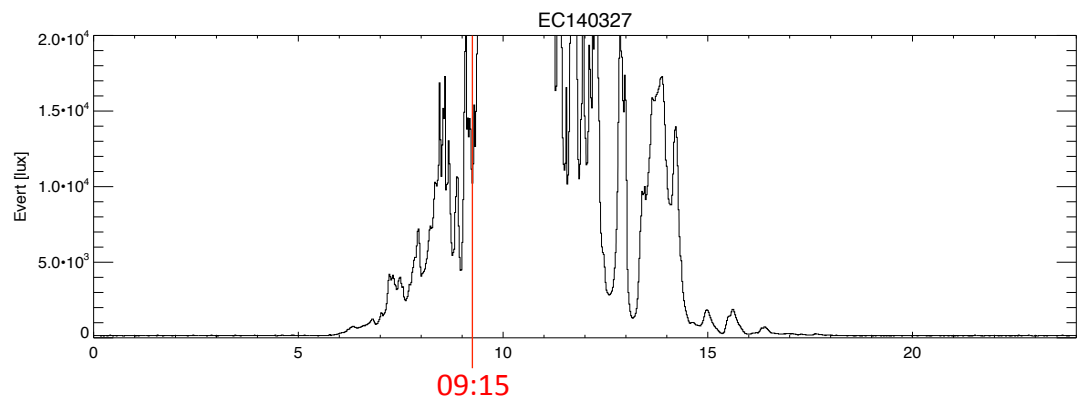
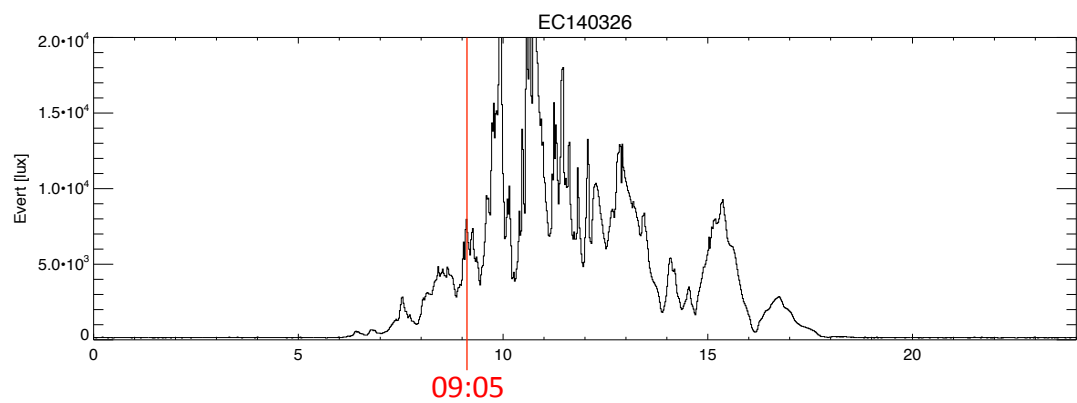
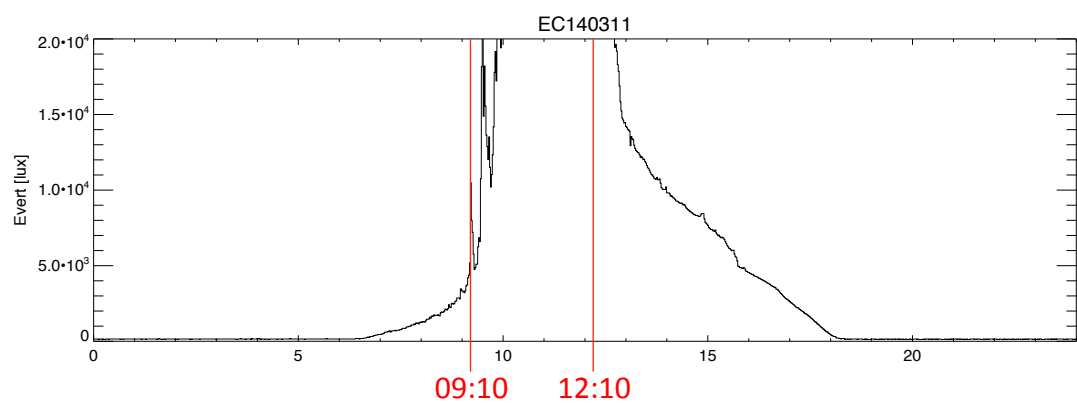
“No change in %T” cases



“No change in %T” cases



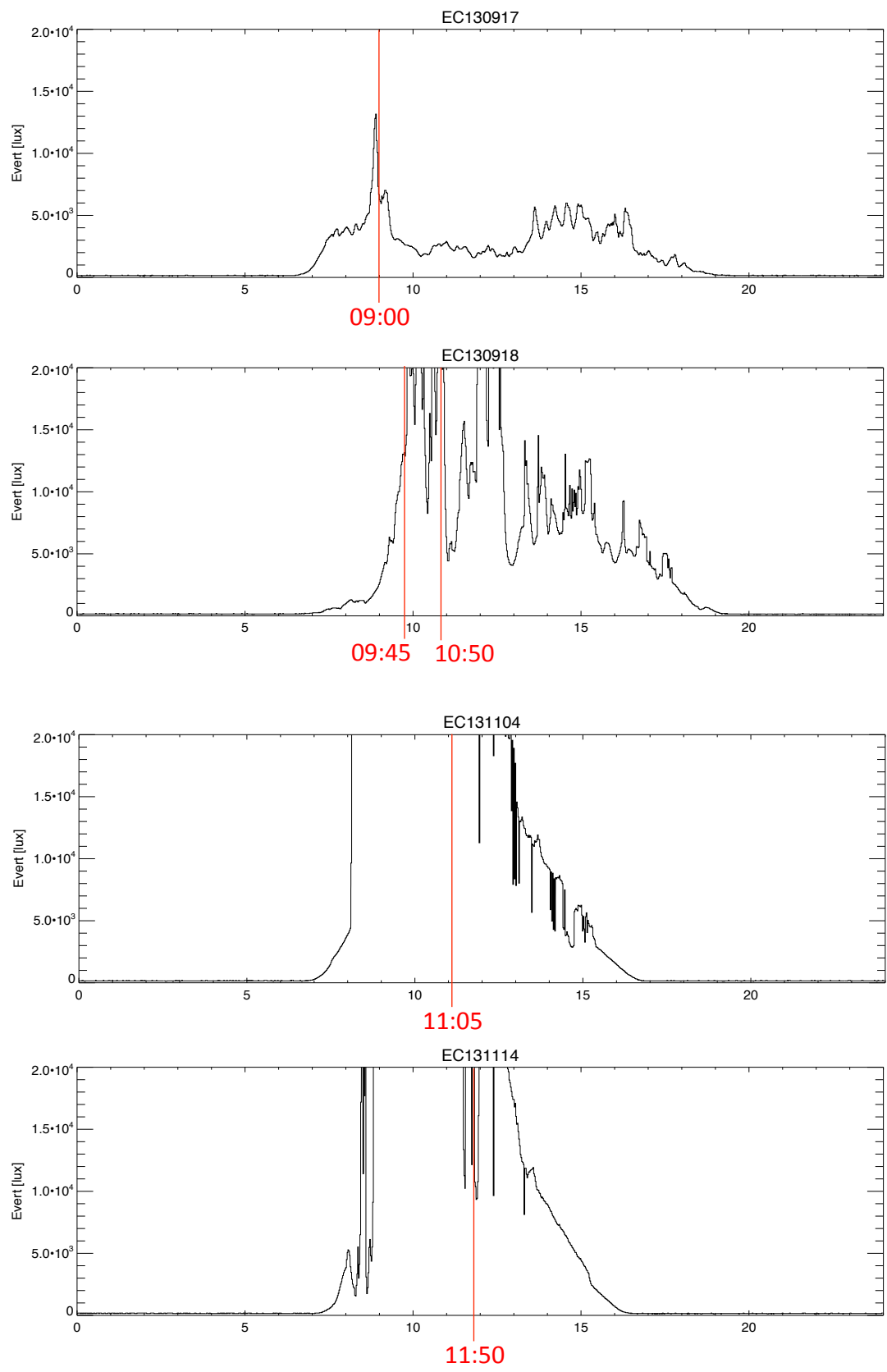
“No change in %T” cases



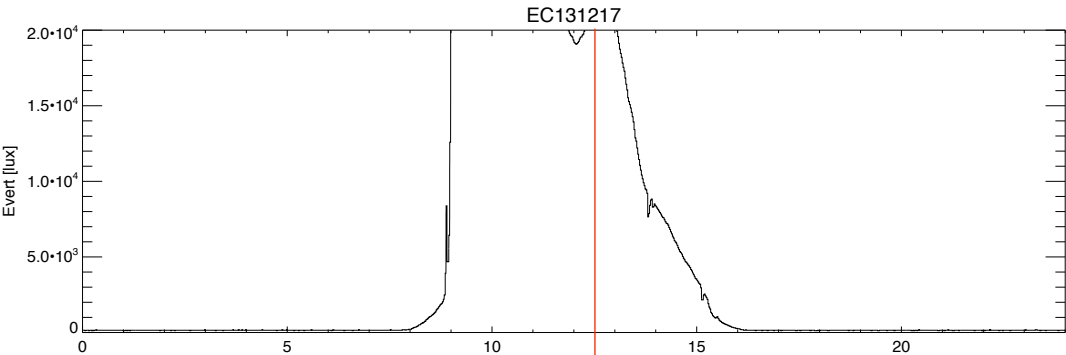
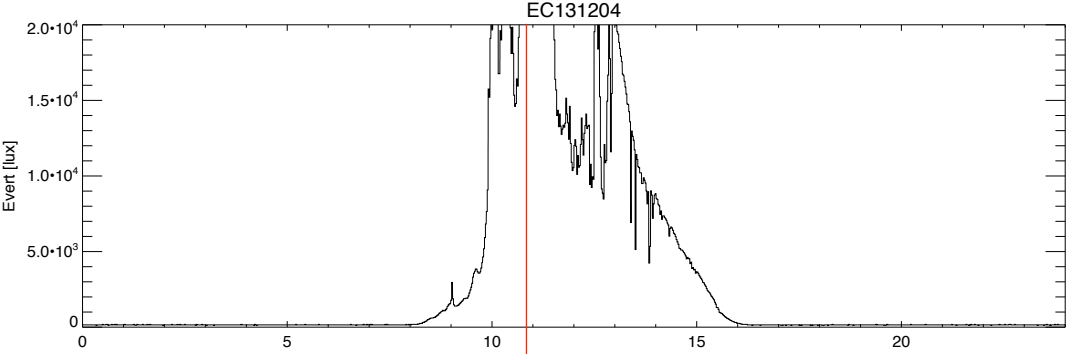
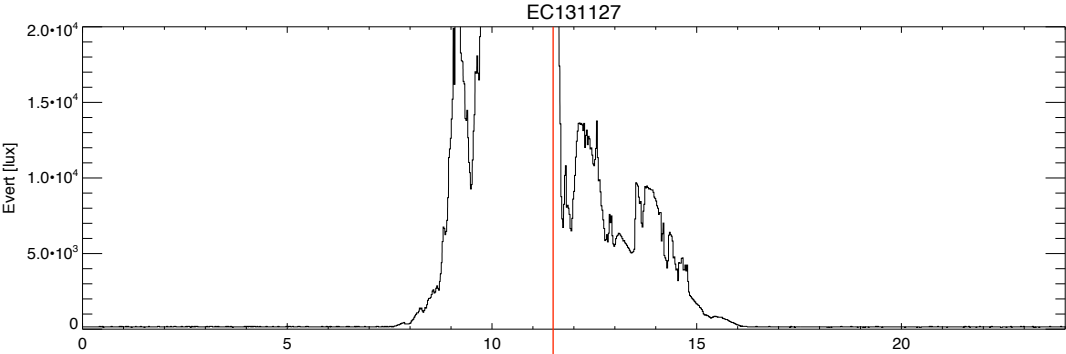
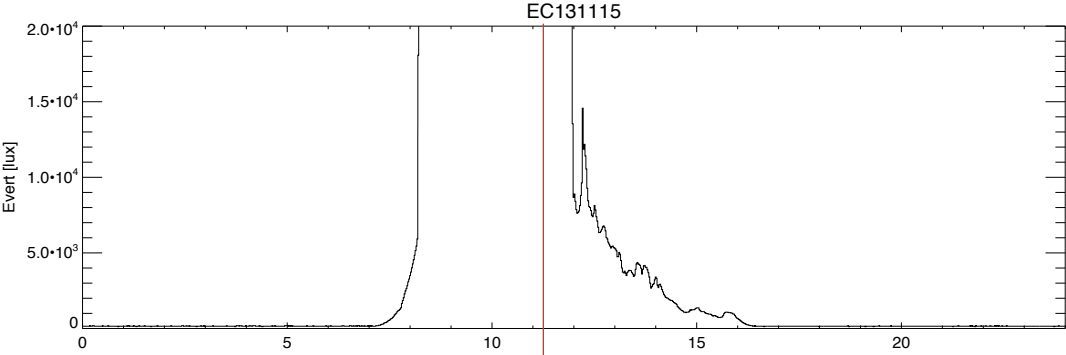
## **Appendix X**

### **Façade sensor analysis for the “increase in %T” cases**

“Increase in %T” cases

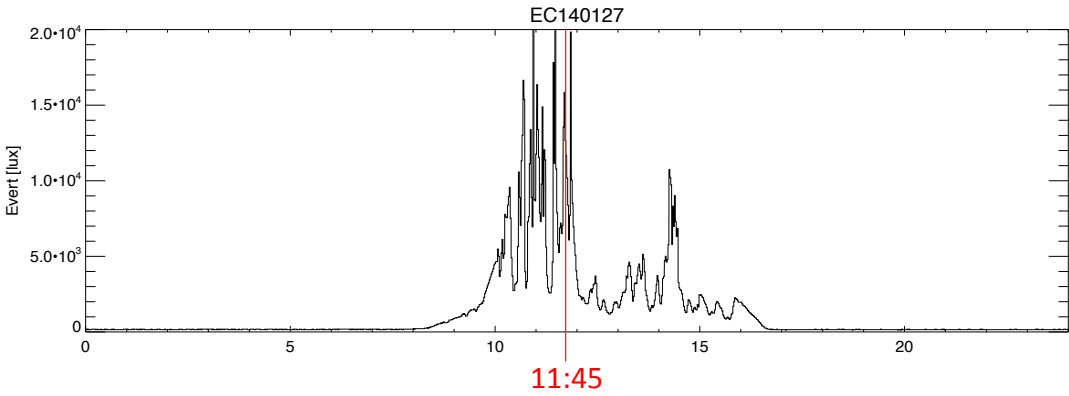
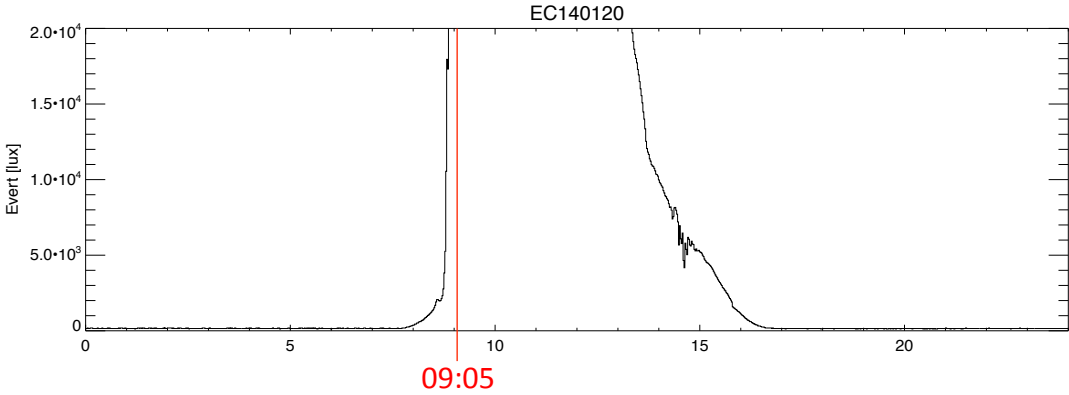
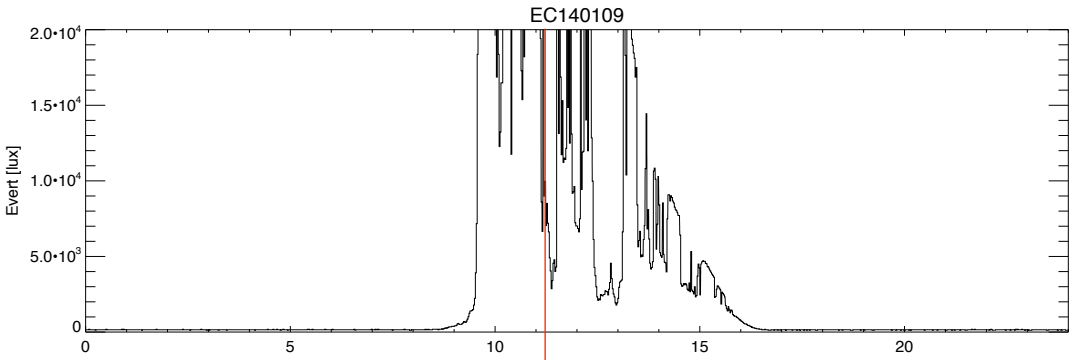
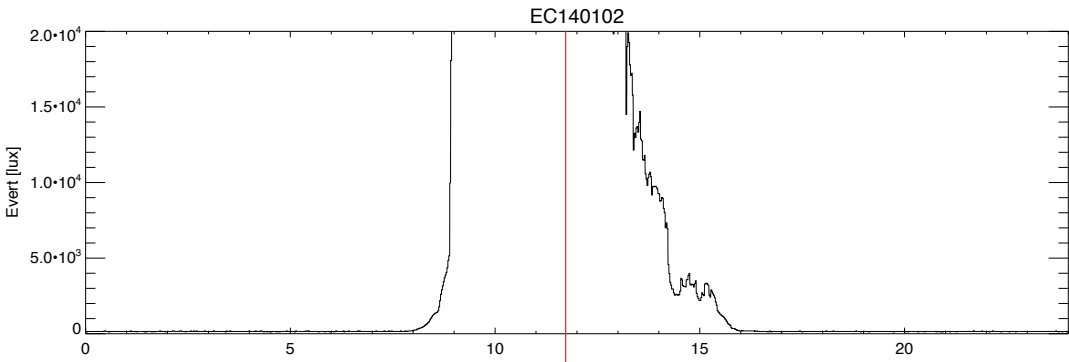


**“Increase in %T” cases**

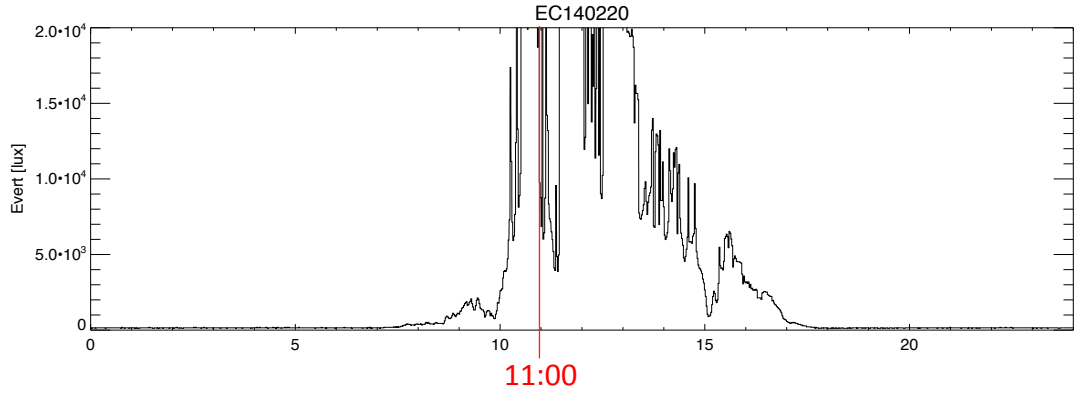
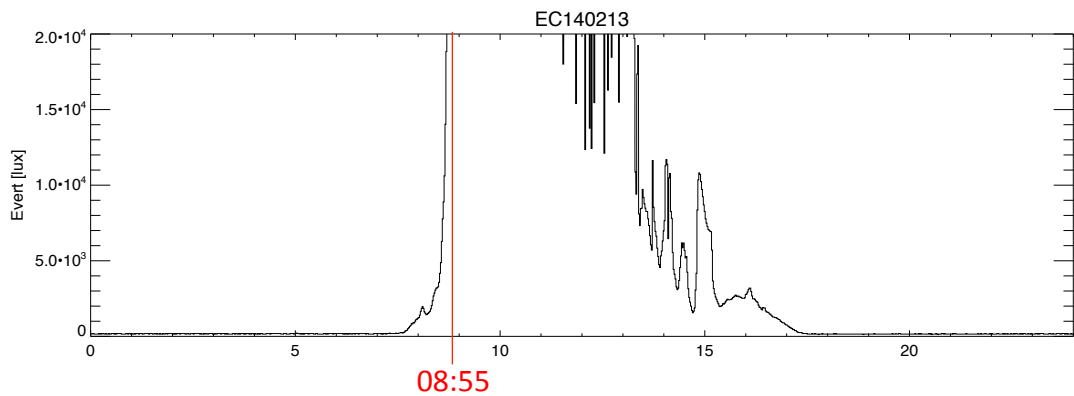
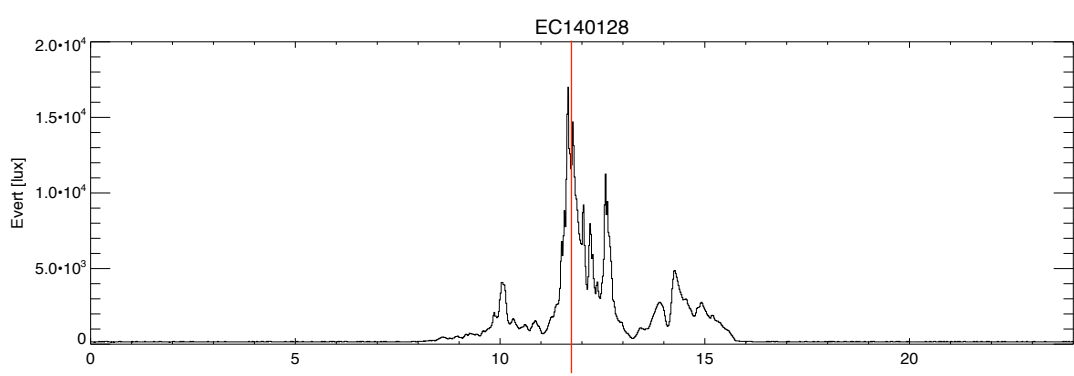




“Increase in %T” cases



**“Increase in %T” cases**

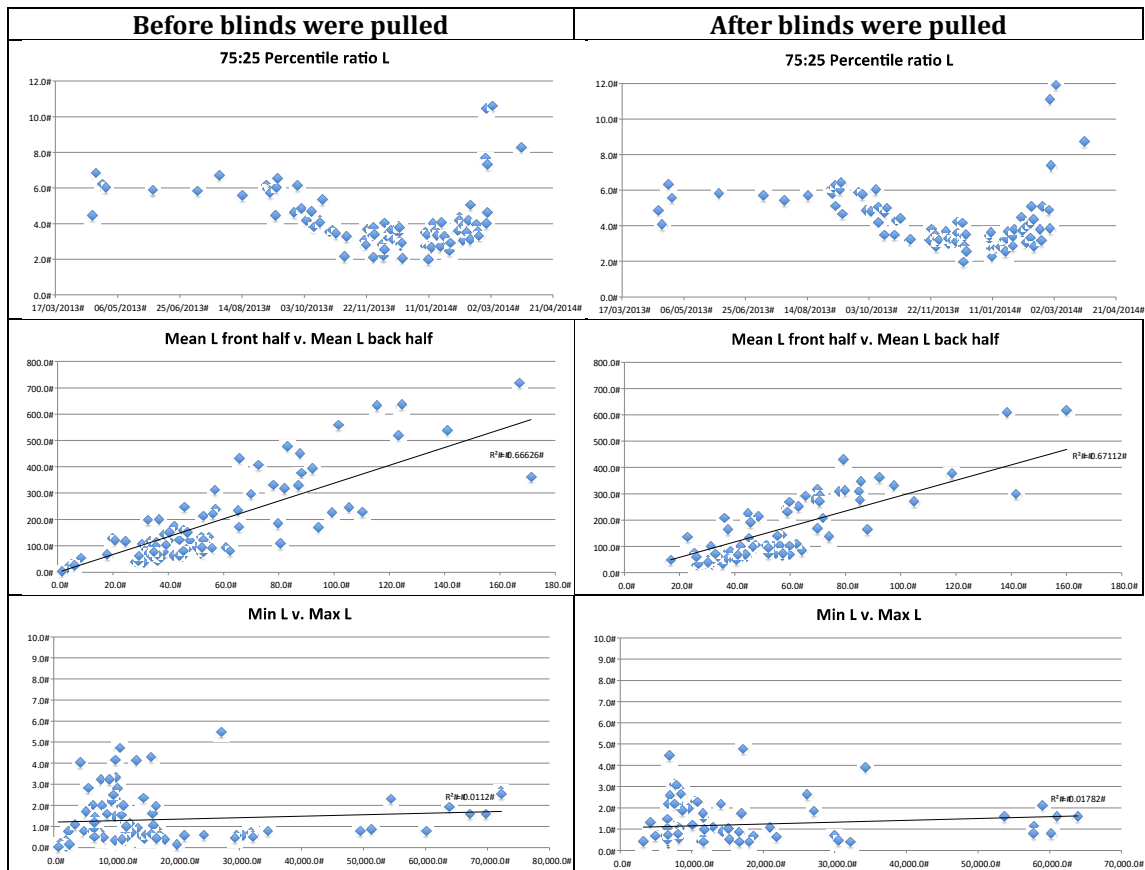


## Appendix XI

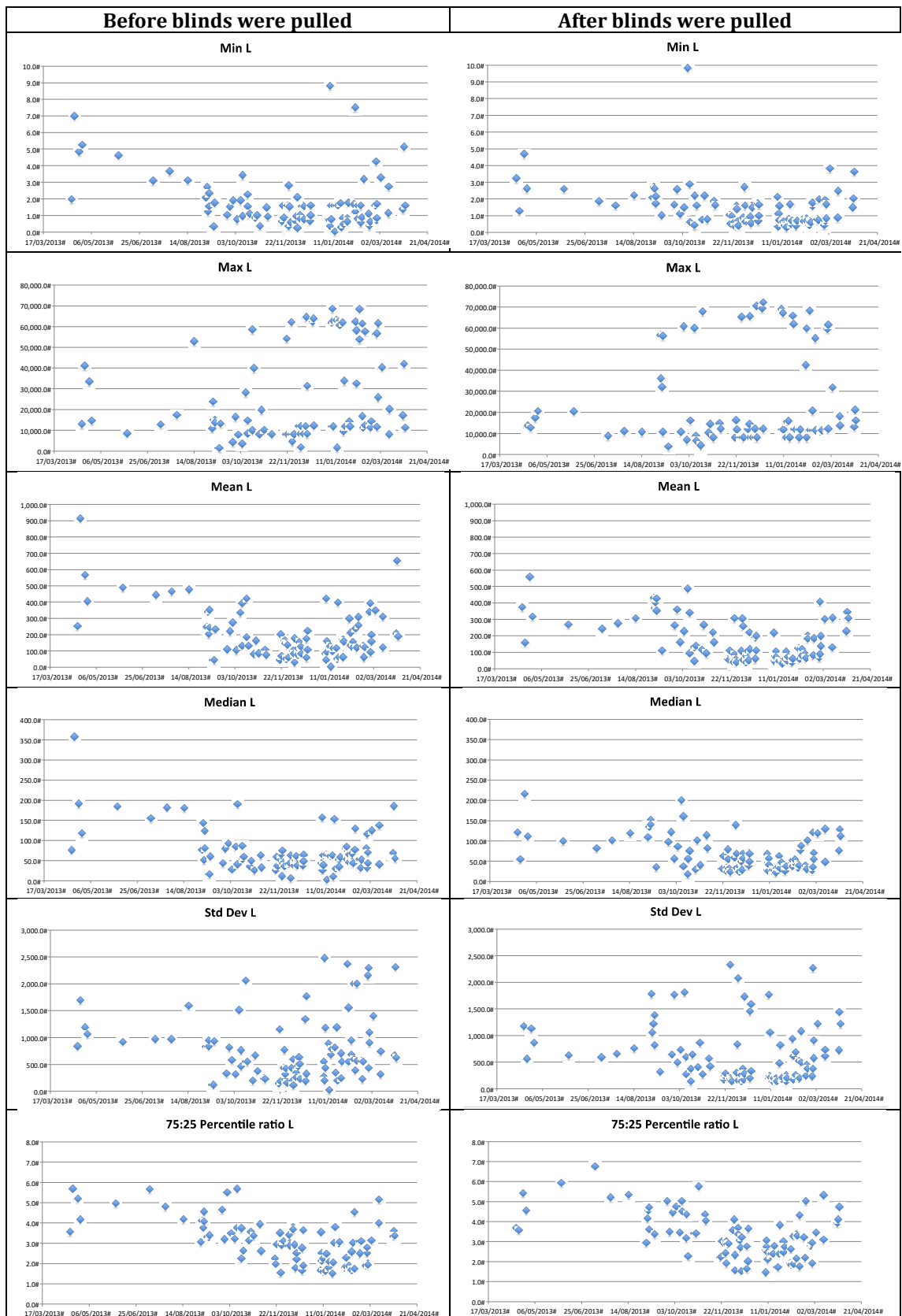
### HDR metrics at times when blinds were used

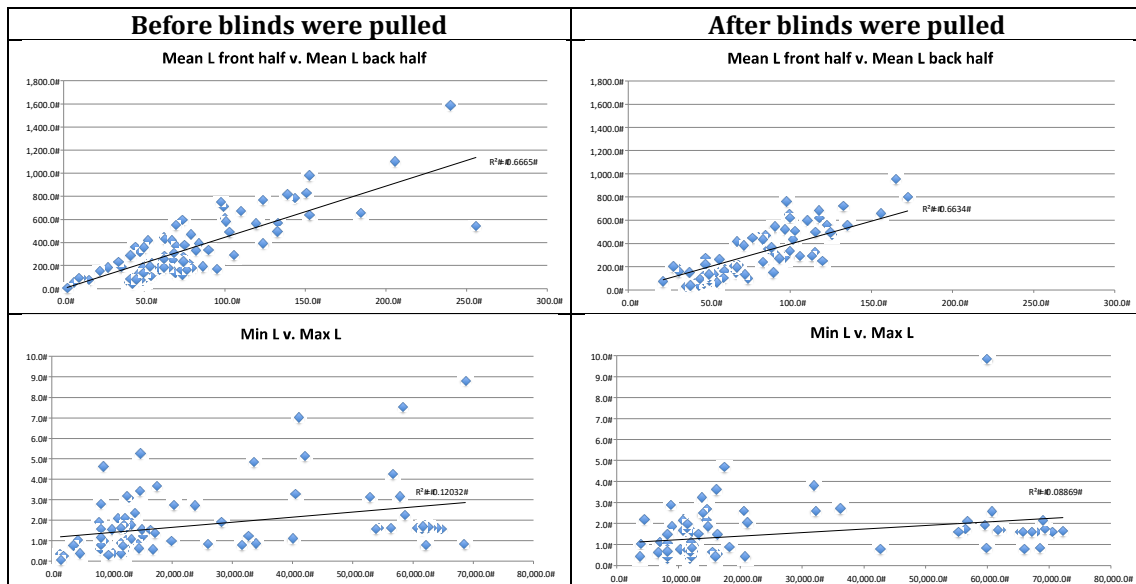
#### Camera HDR1





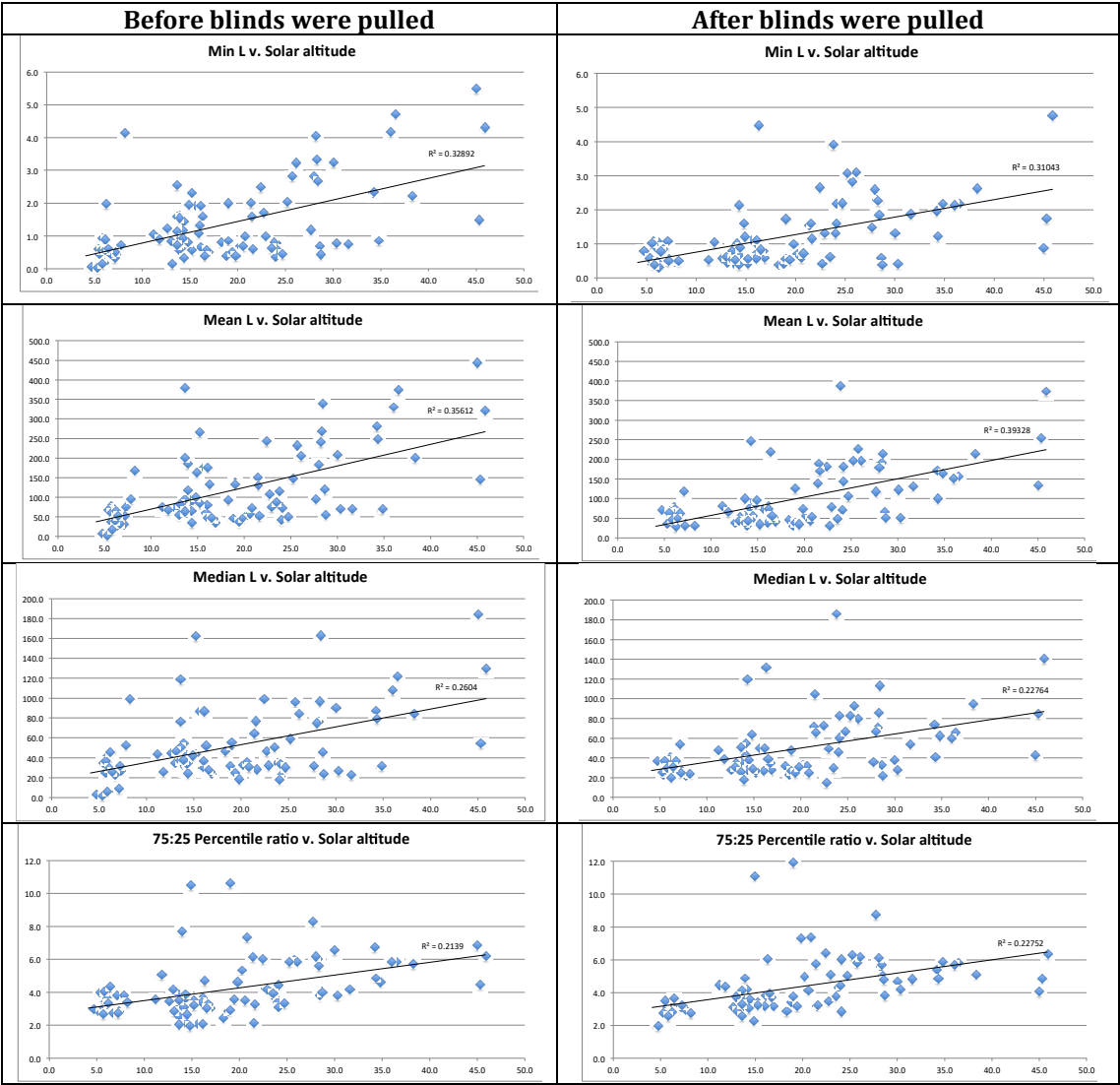
## Camera HDR2



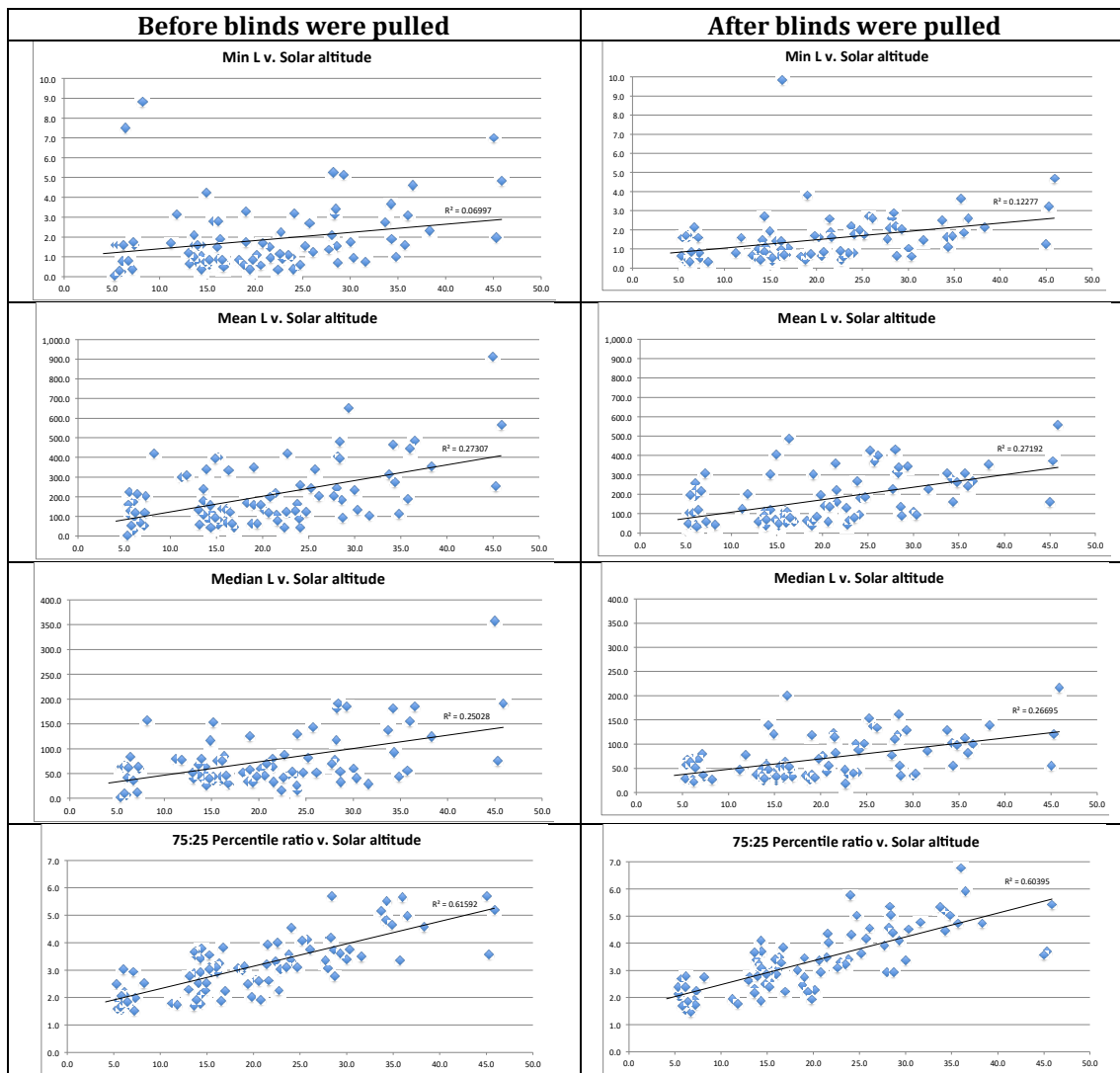


HDR metrics plotted against solar altitude

Camera HDR1



## Camera HDR2

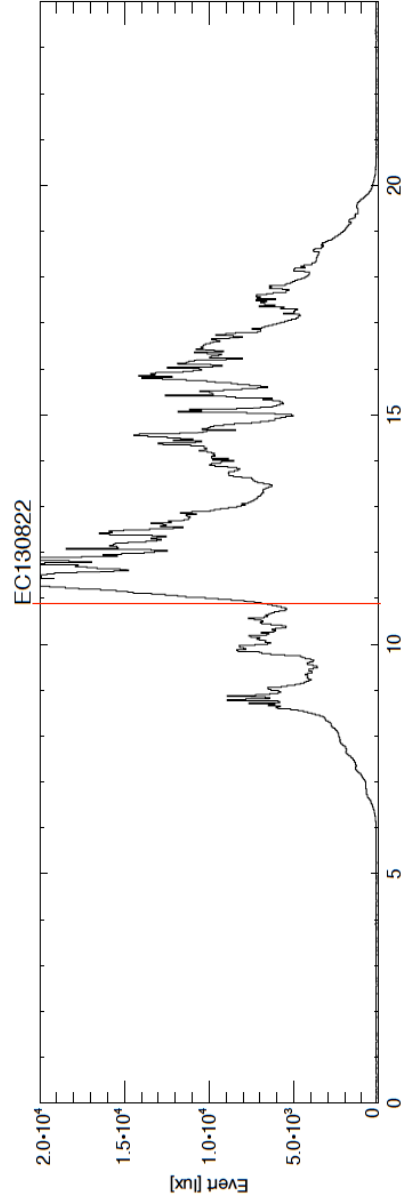
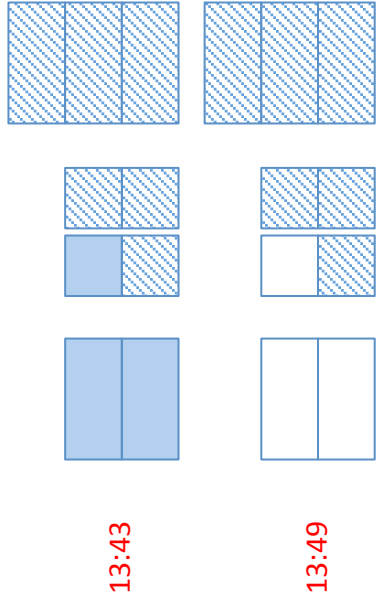
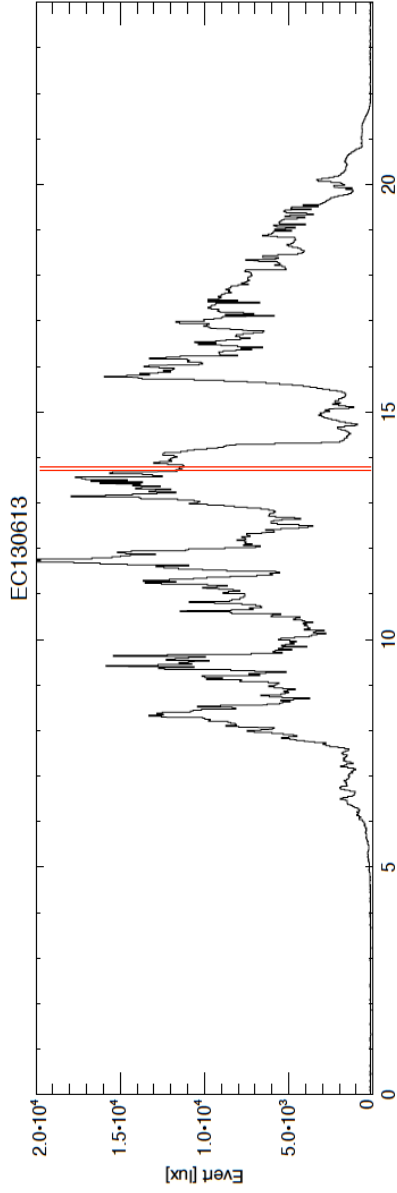
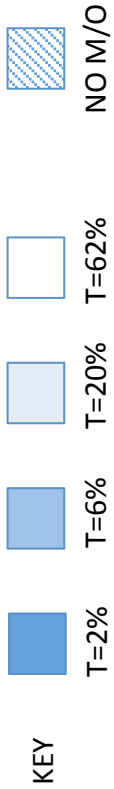


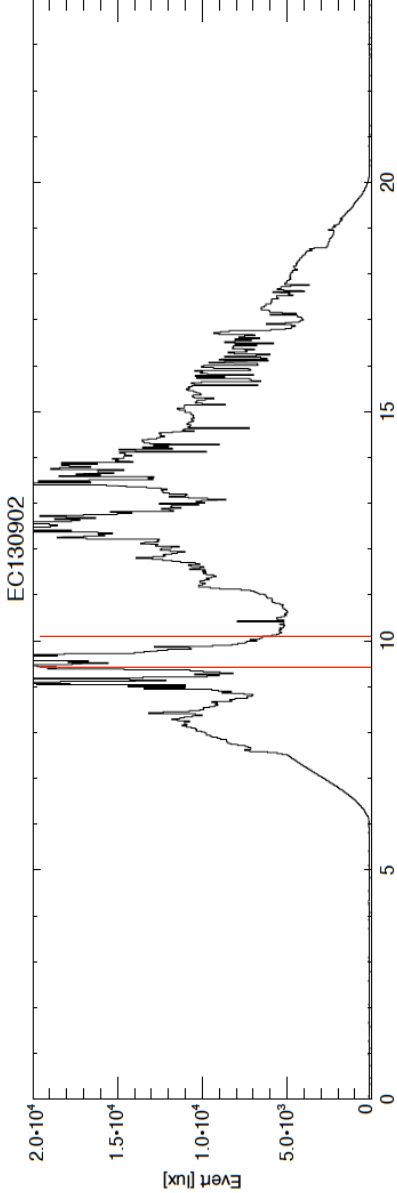
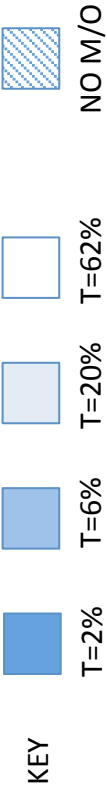


## **Appendix XII**

### **Façade sensor profiles at times of manual override**

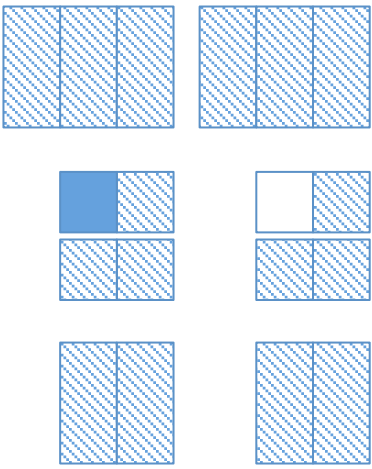
Note that exterior sensor profiles for April 2013 were not available in the required format, and there were no manual overrides in May 2013, hence the analysis starts with June 2013.



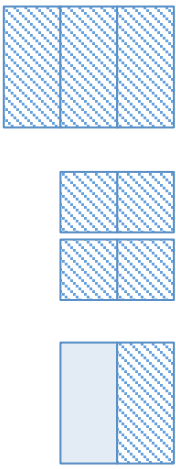
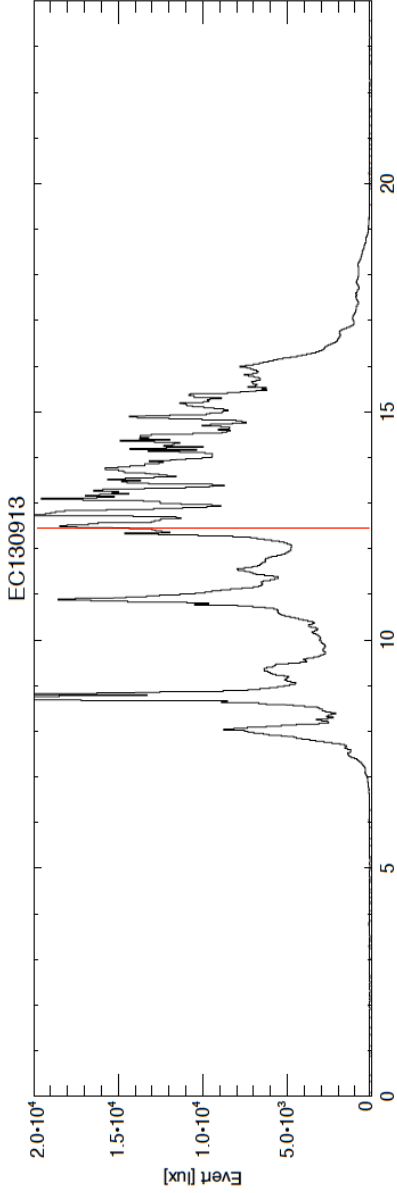


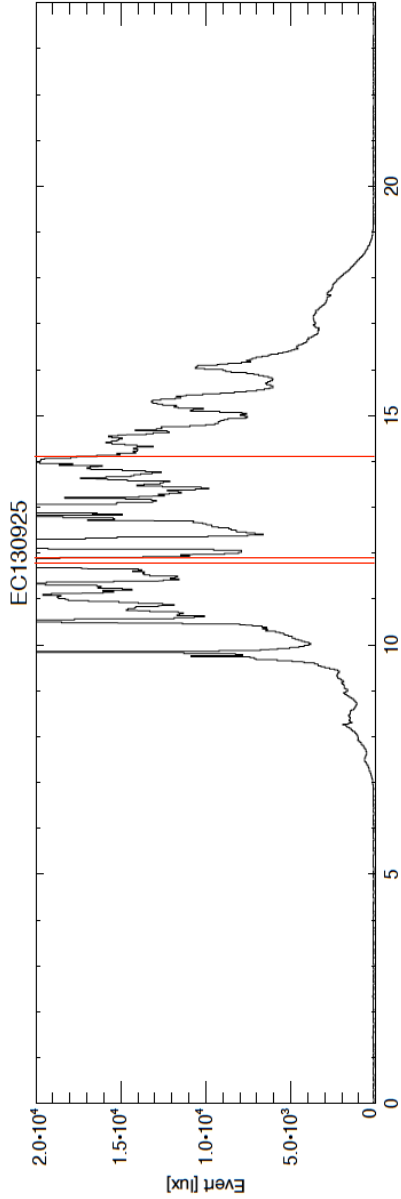
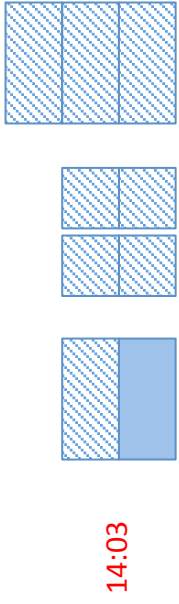
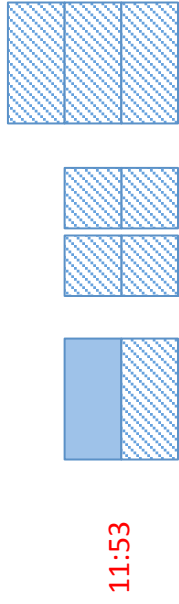
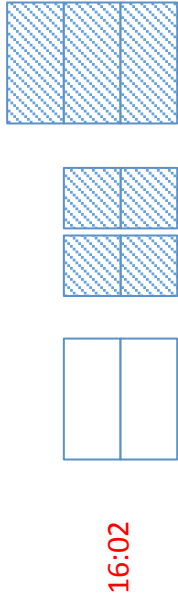
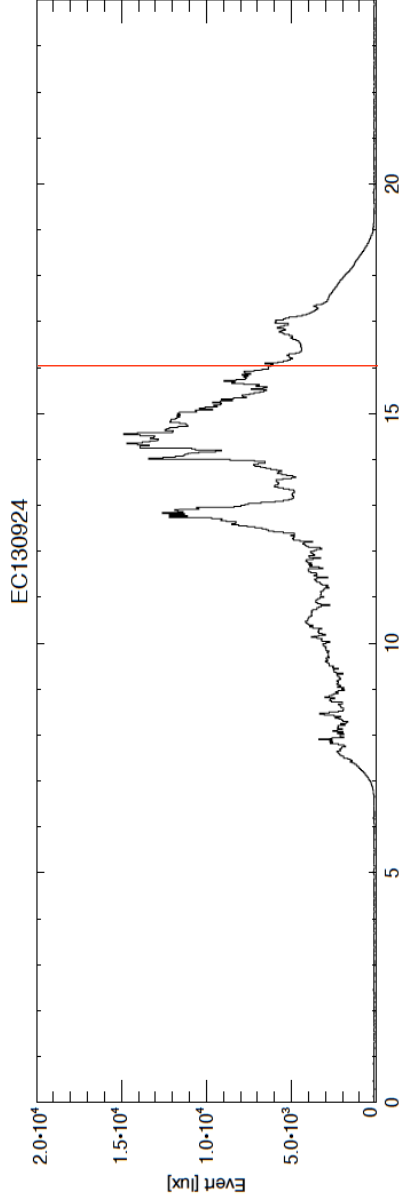
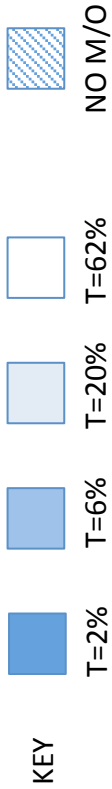
09:26

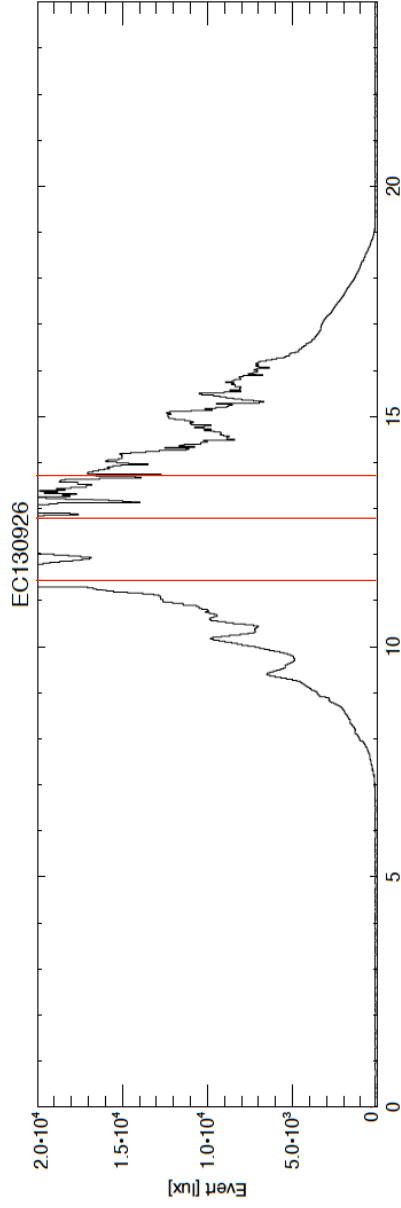
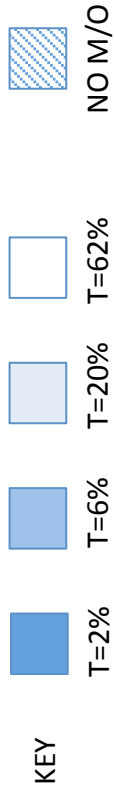
10:05



12:26



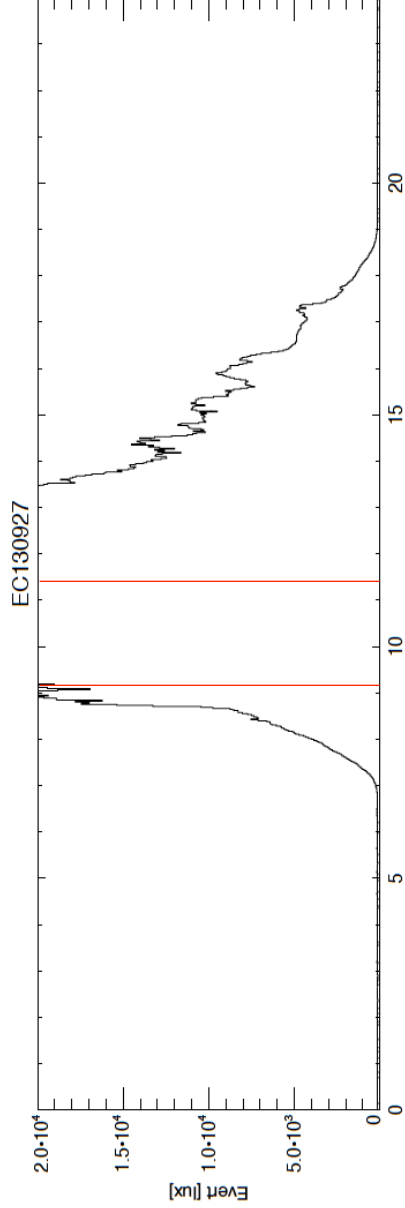




11:25

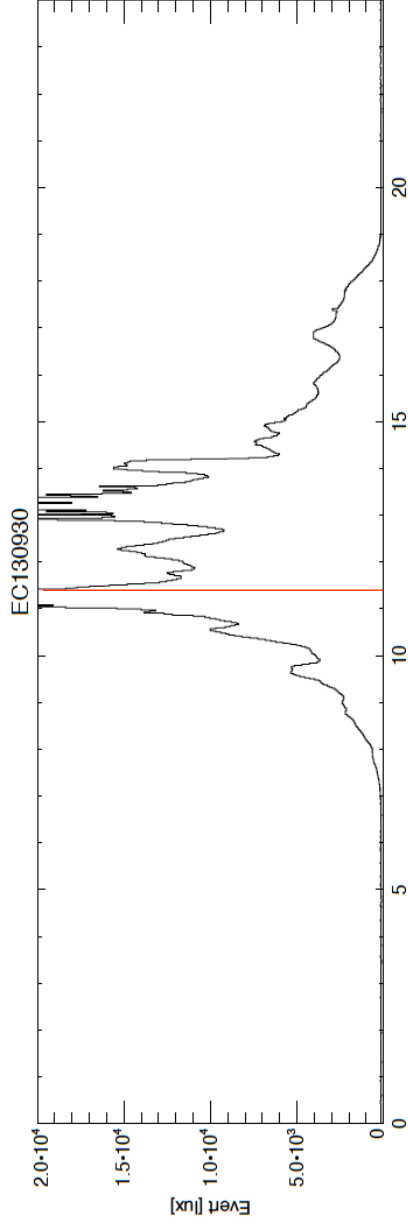
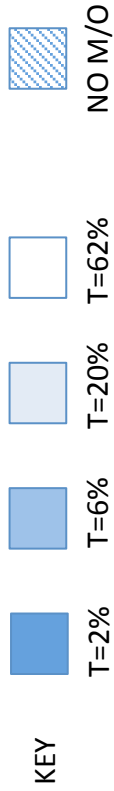
12:45

13:38

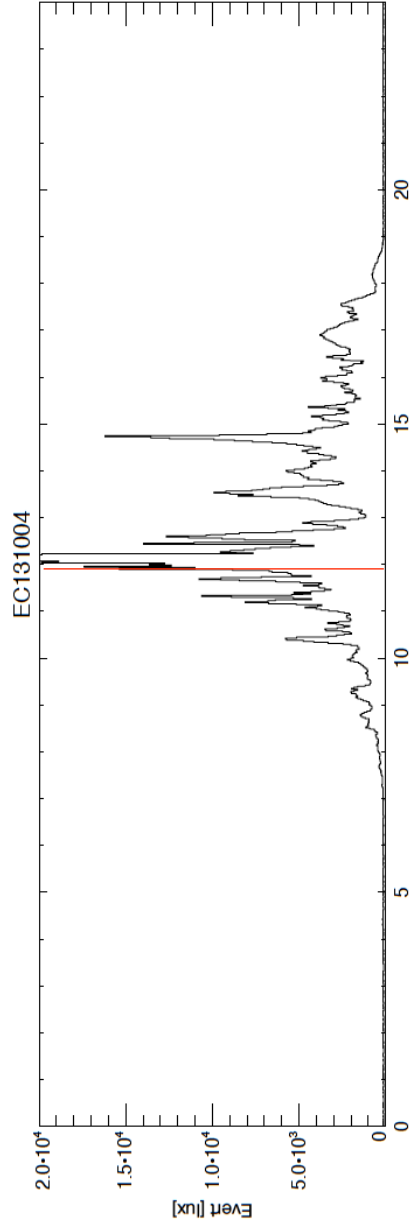
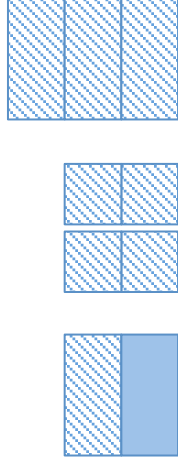


09:08

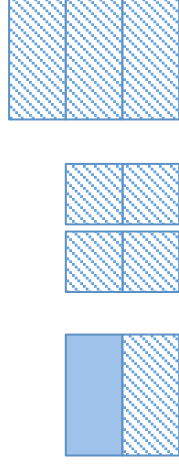
11:20

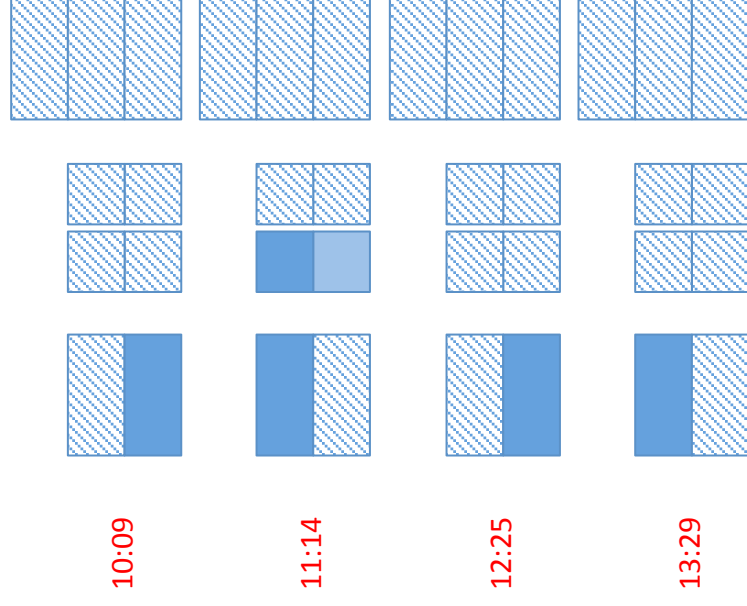
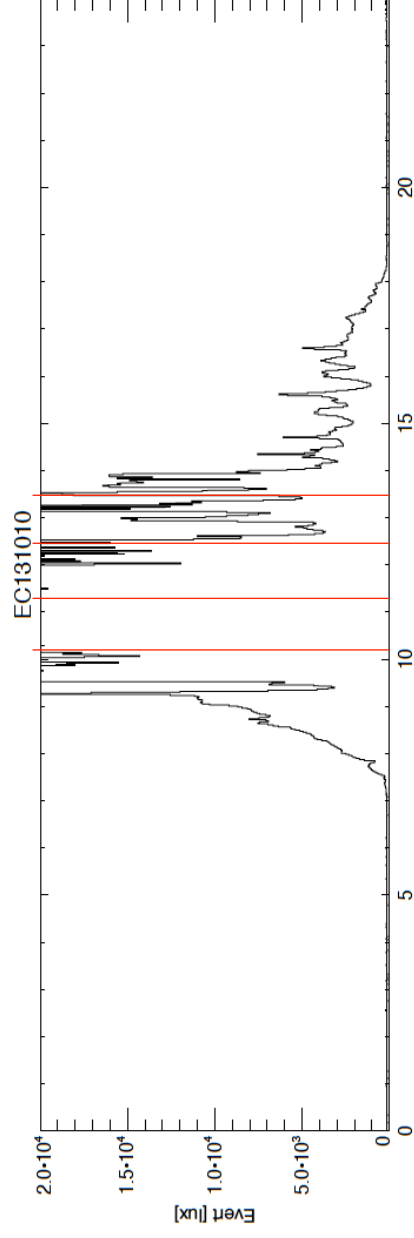
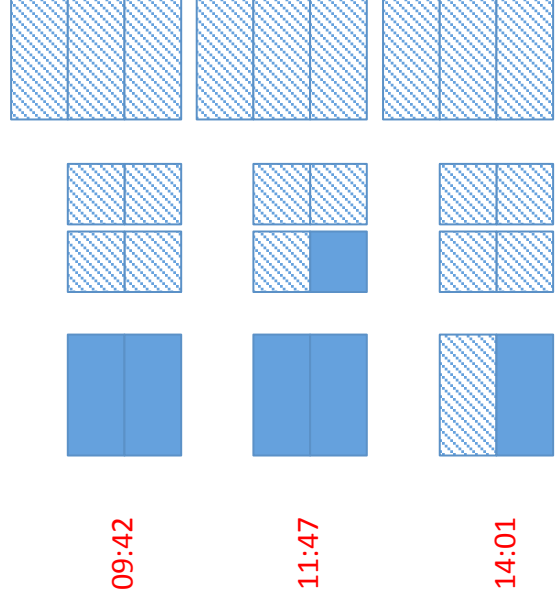
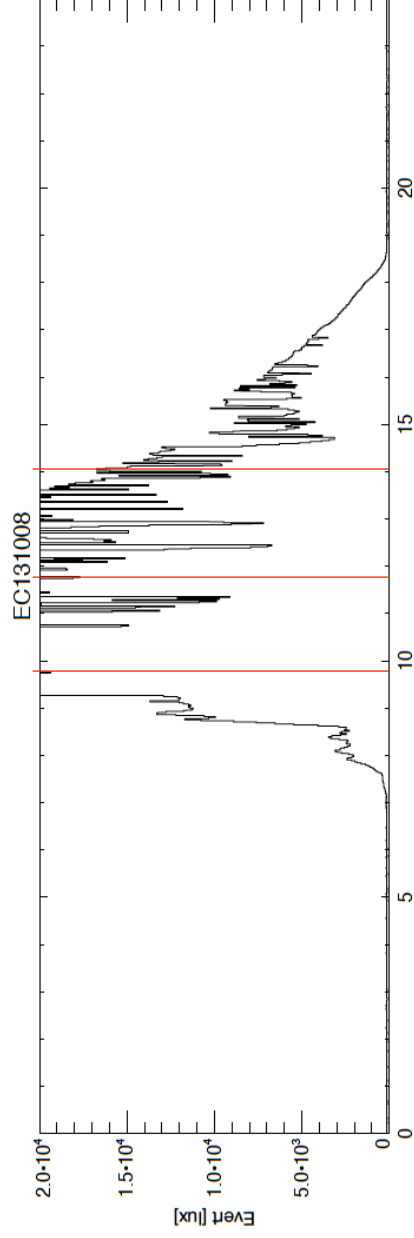
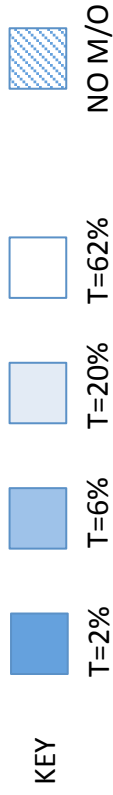


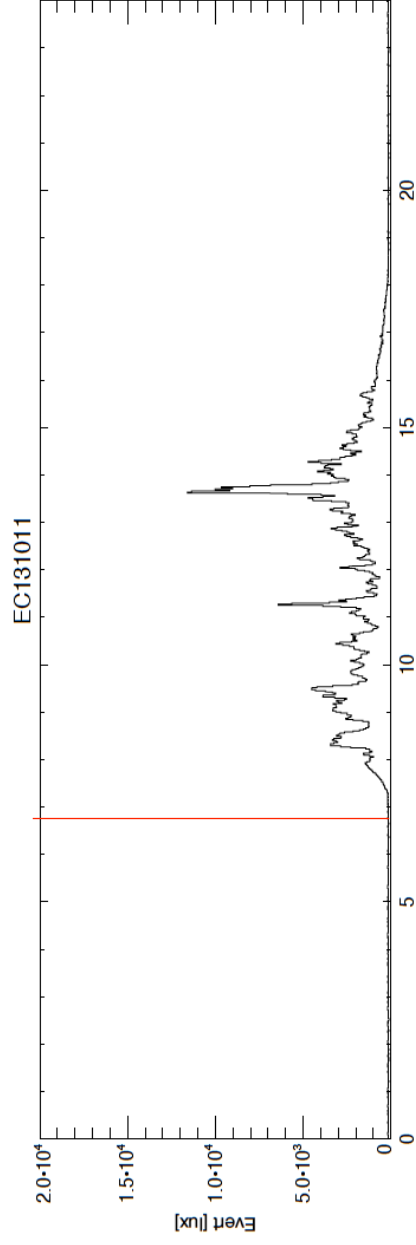
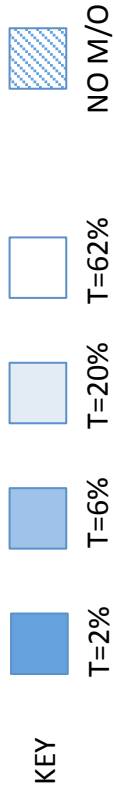
11:17



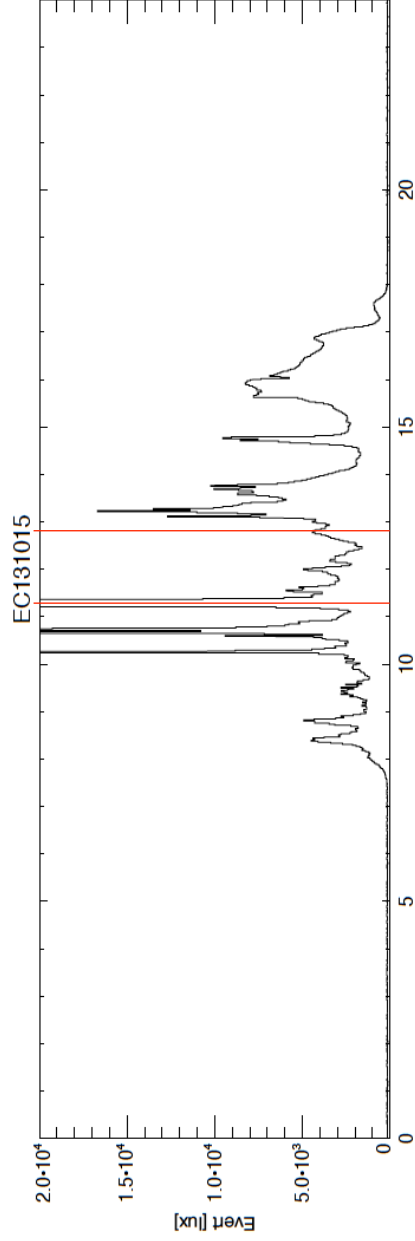
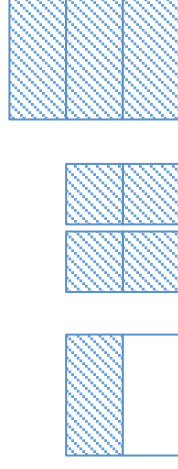
11:53



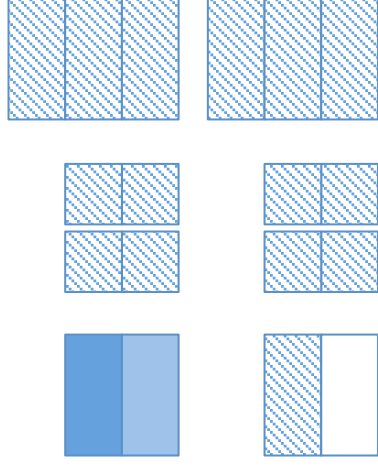




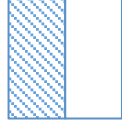
06:45



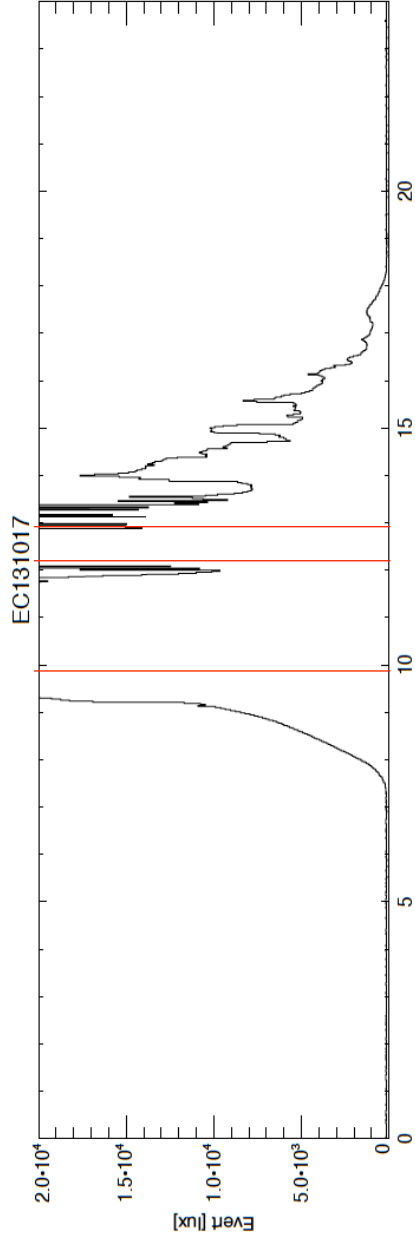
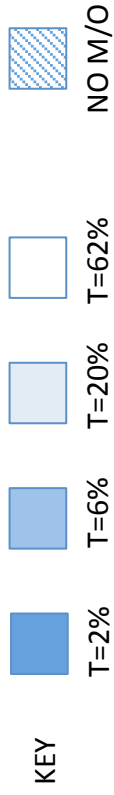
11:12



12:49



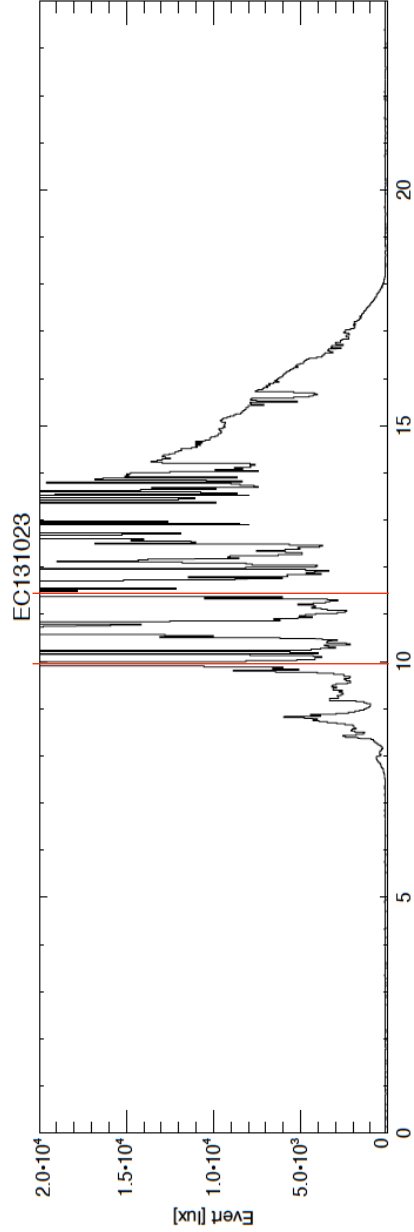
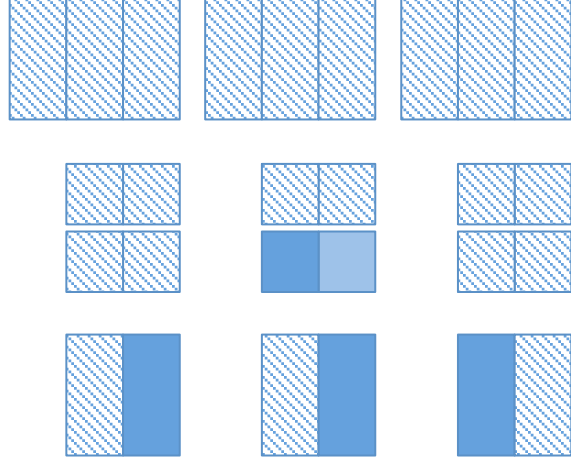




09:53

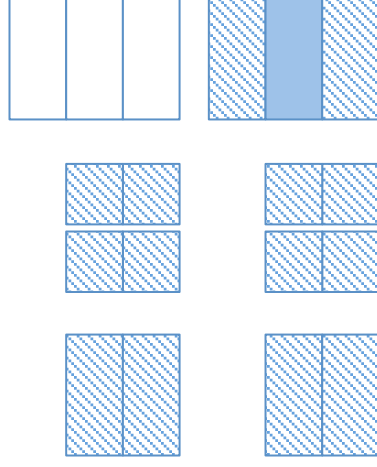
12:08

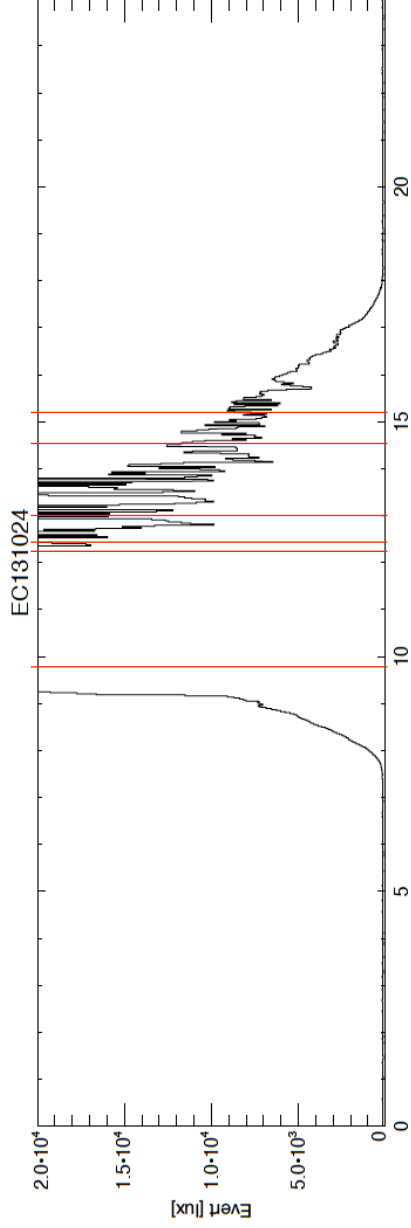
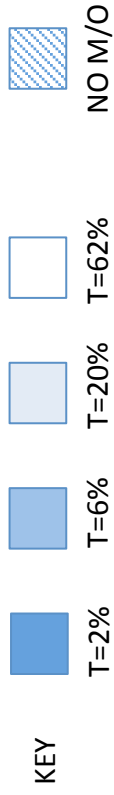
12:55



09:59

11:25





09:47

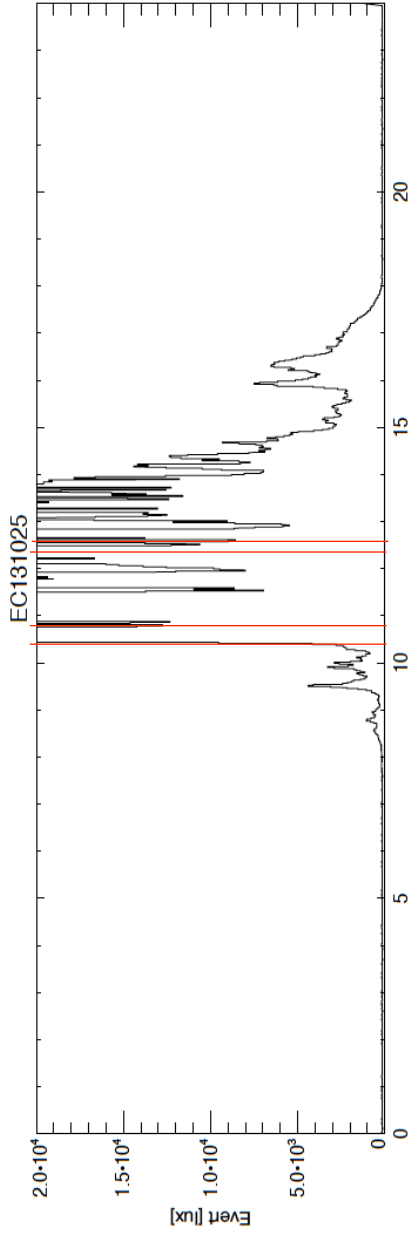
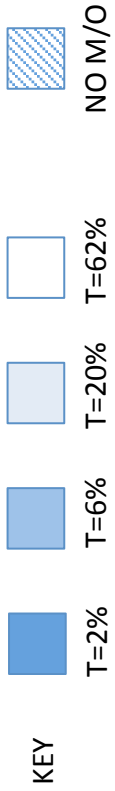
12:11

12:28

13:00

14:34

15:09

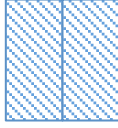
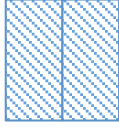
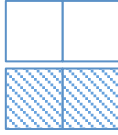
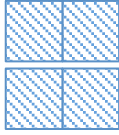
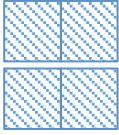
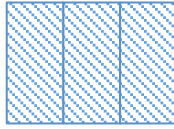
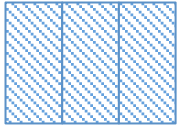


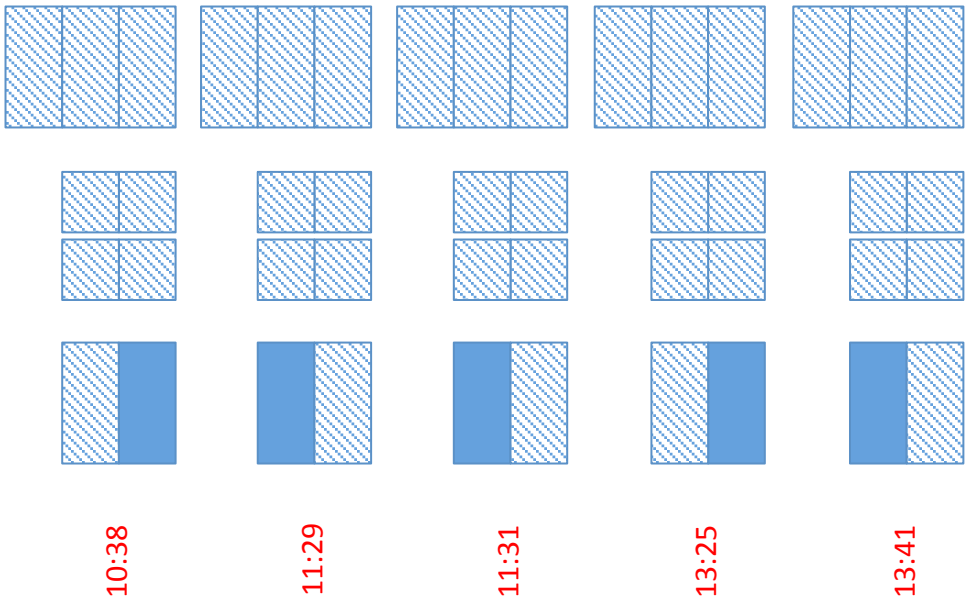
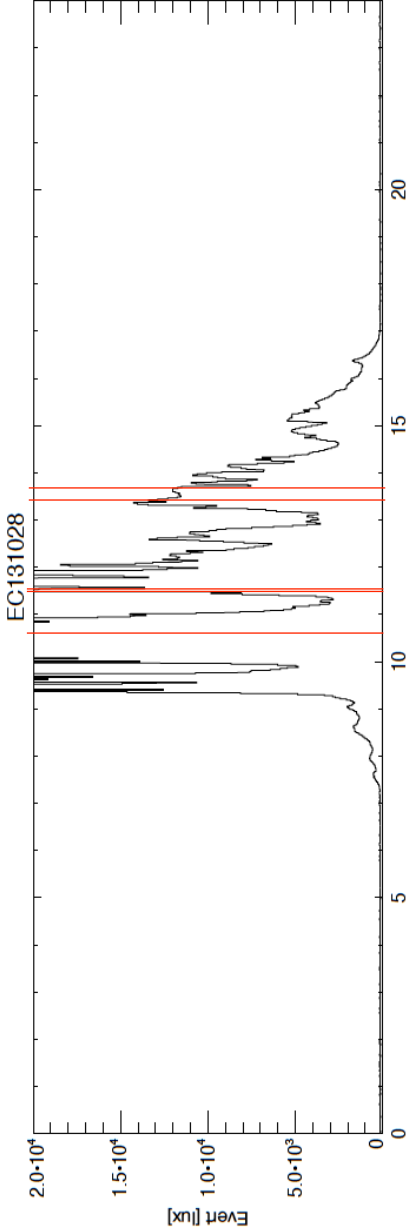
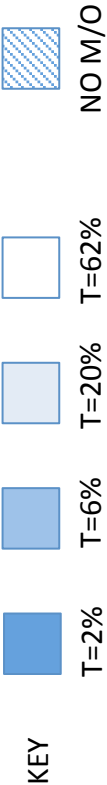
10:26

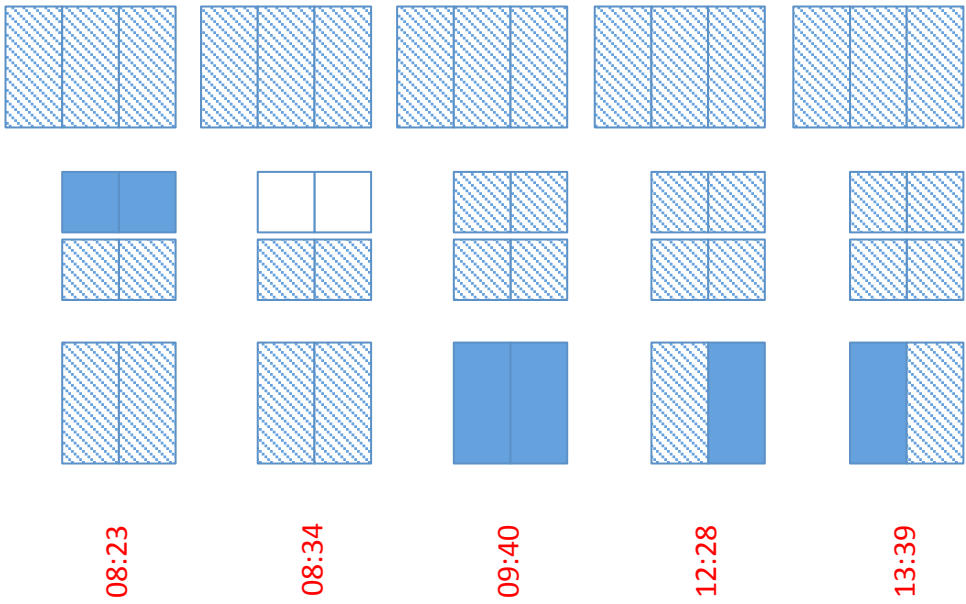
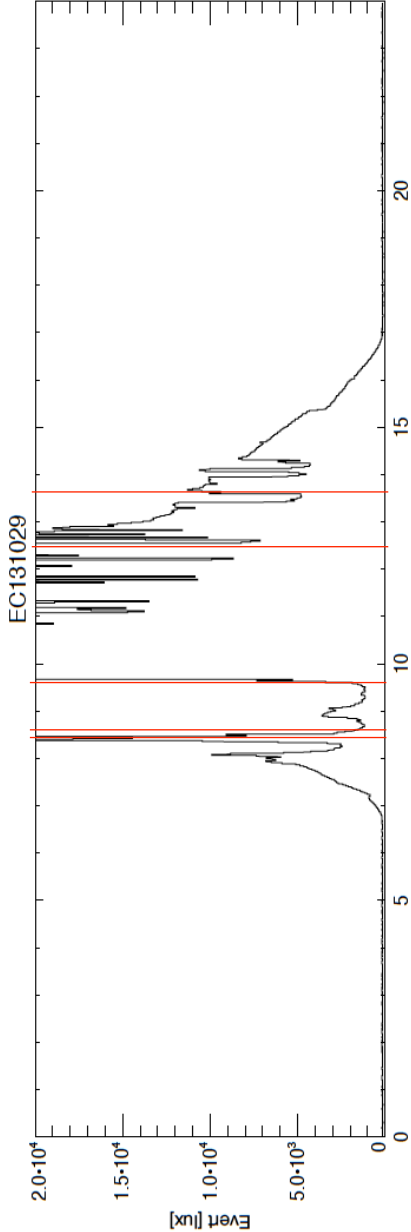
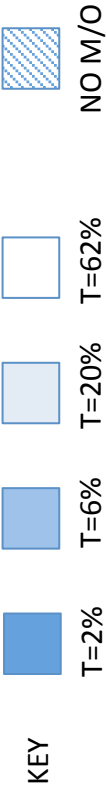
10:46

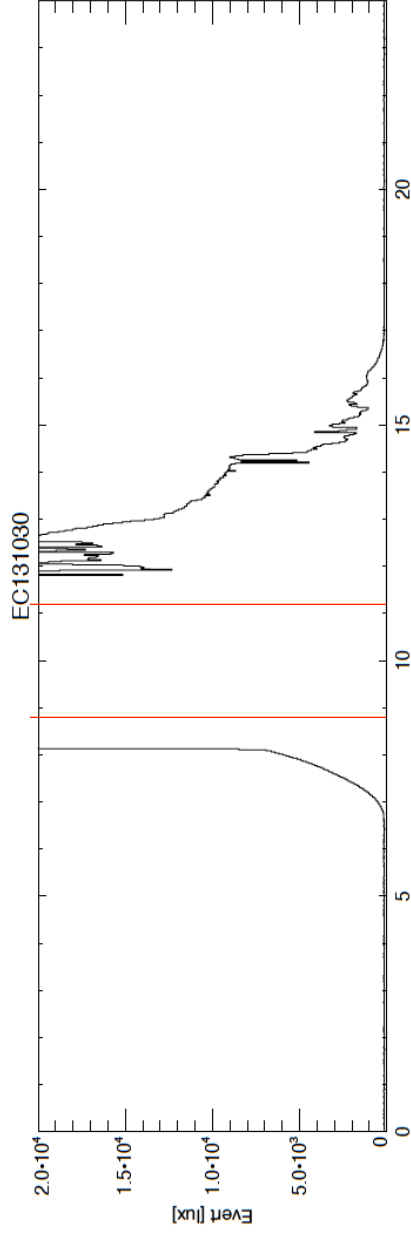
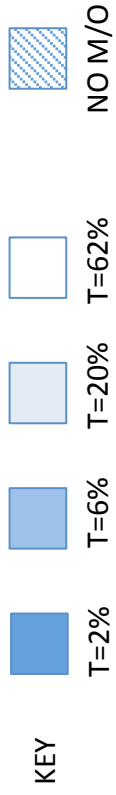
12:19

12:36



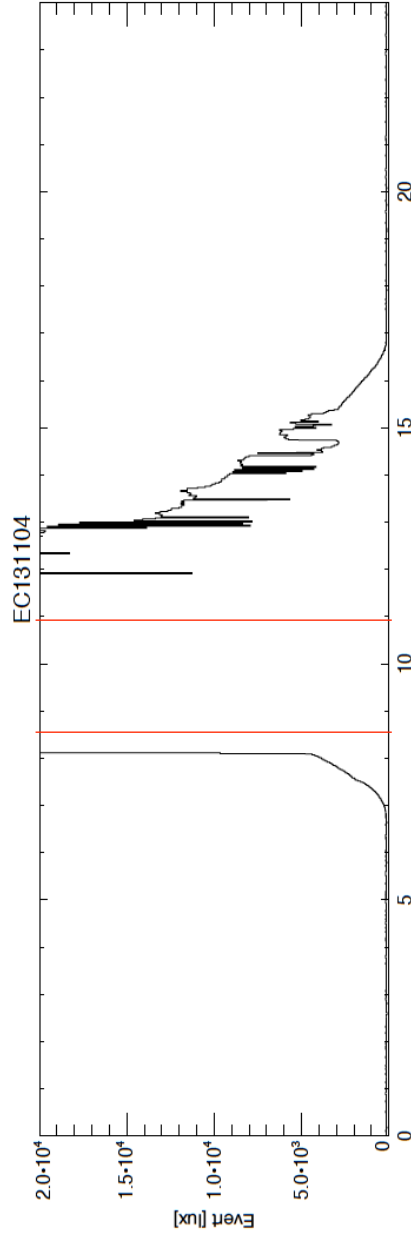
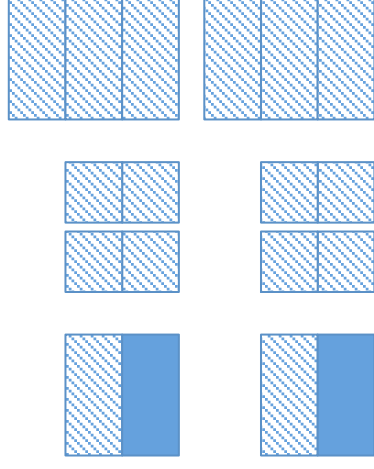






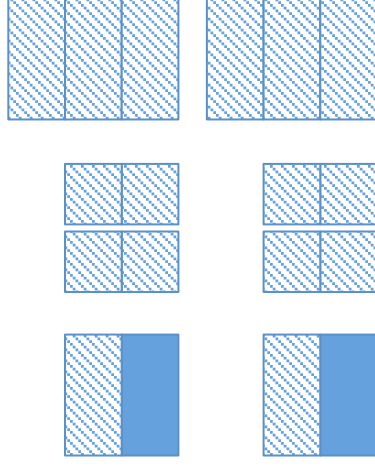
08:48

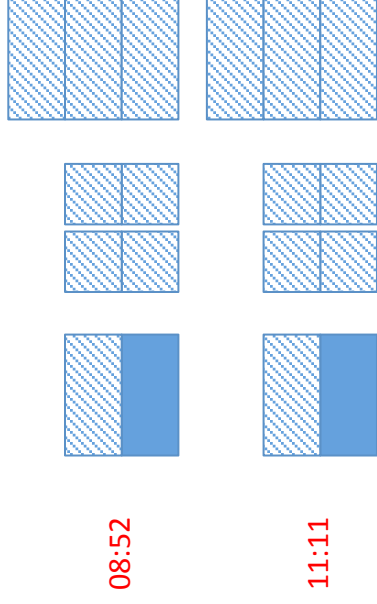
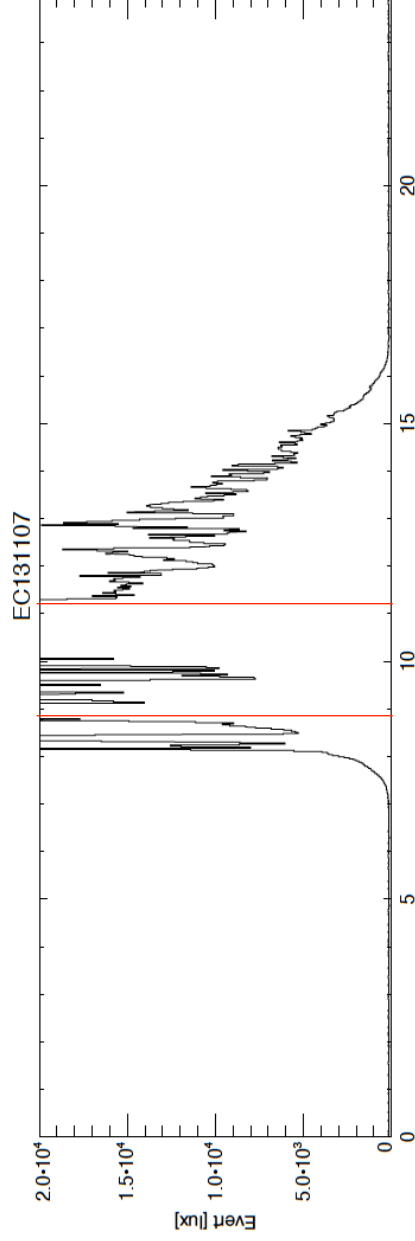
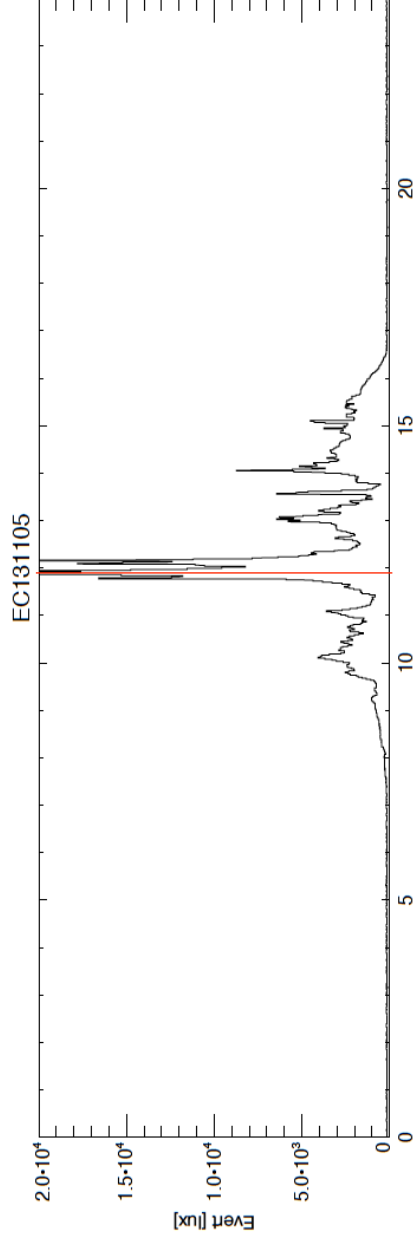
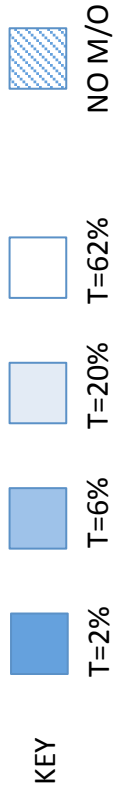
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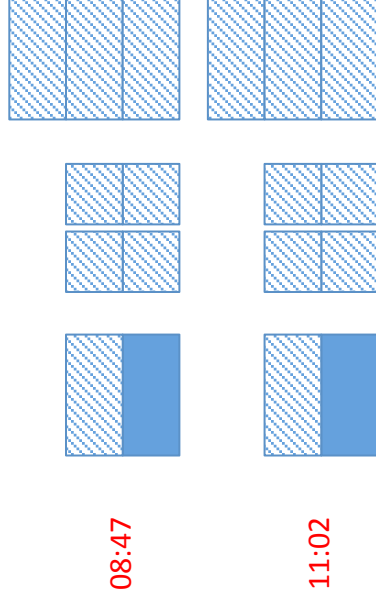
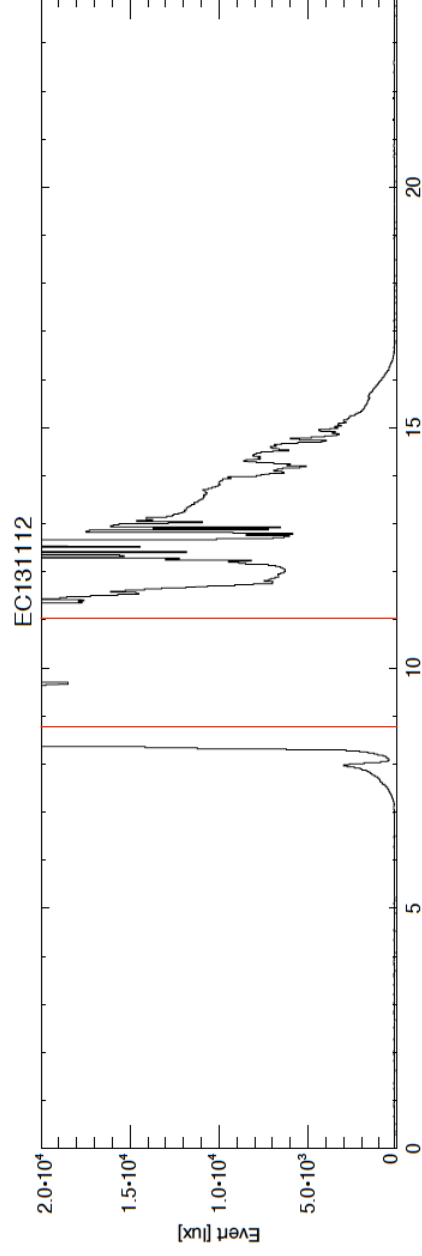
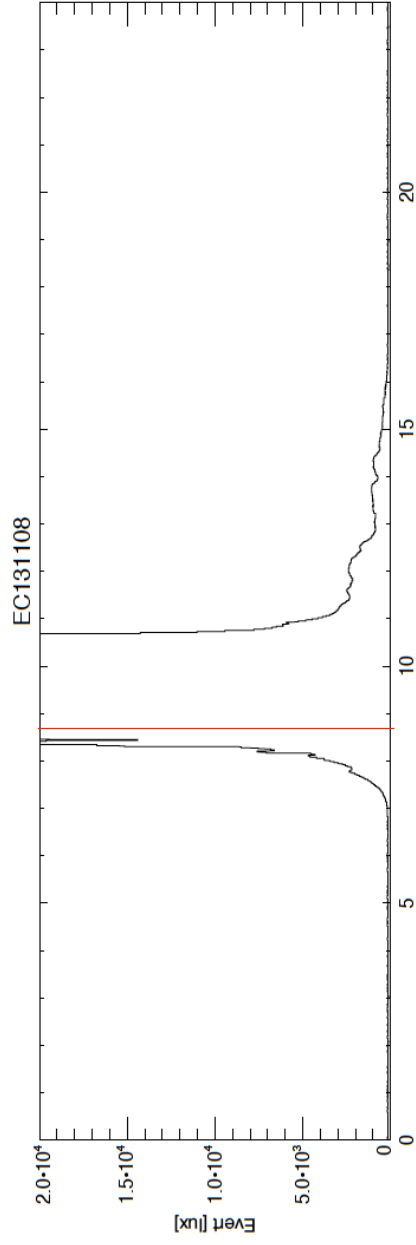
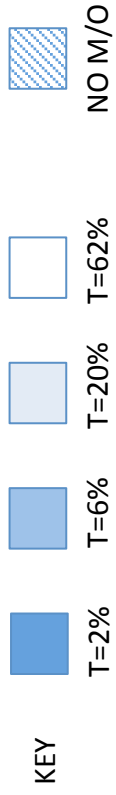


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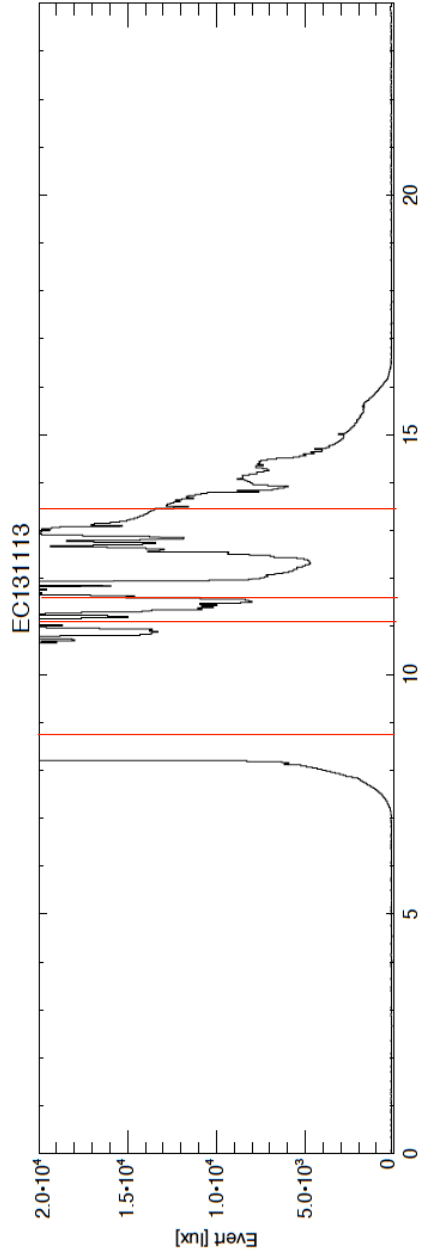
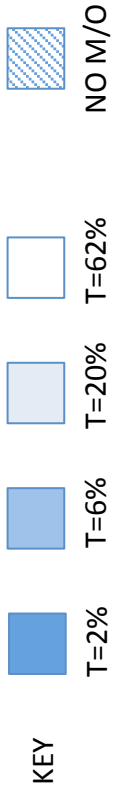
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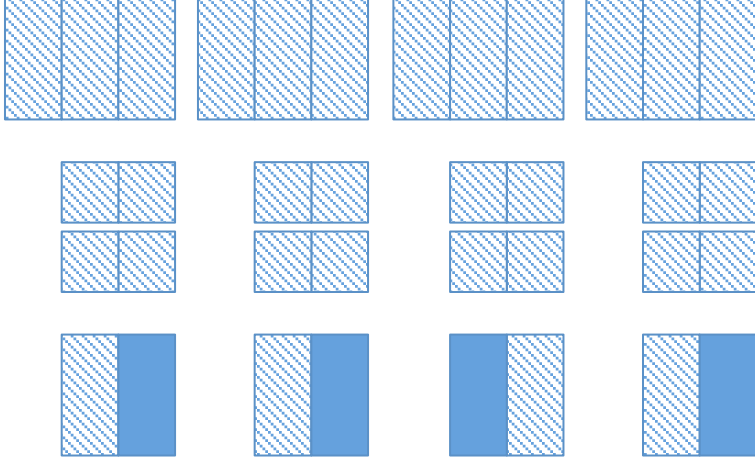


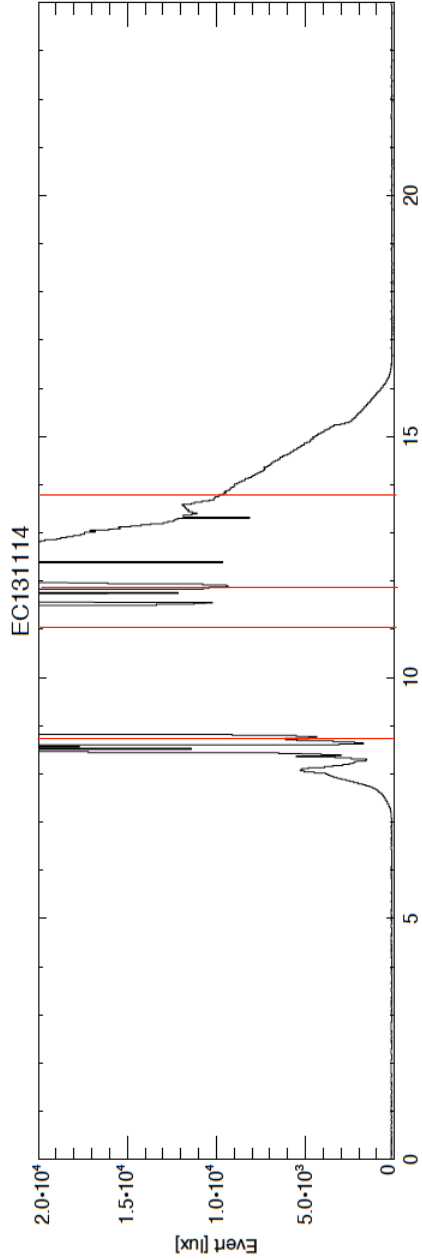
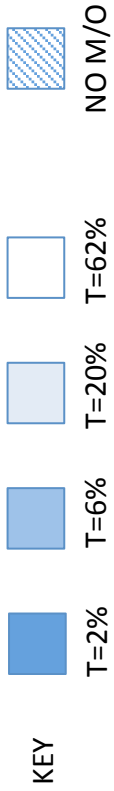
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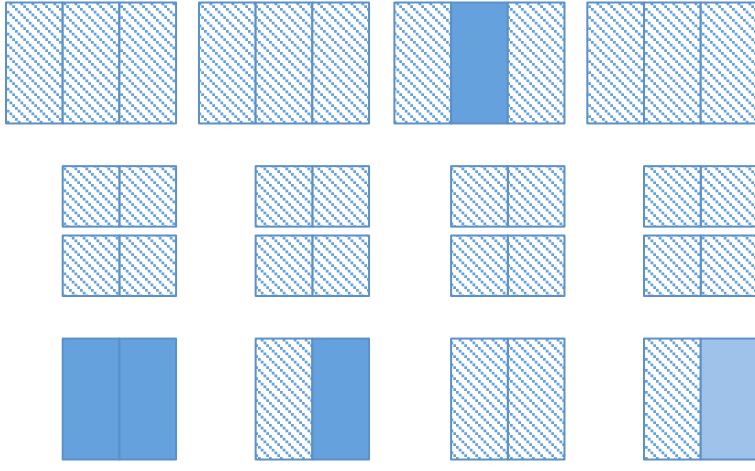


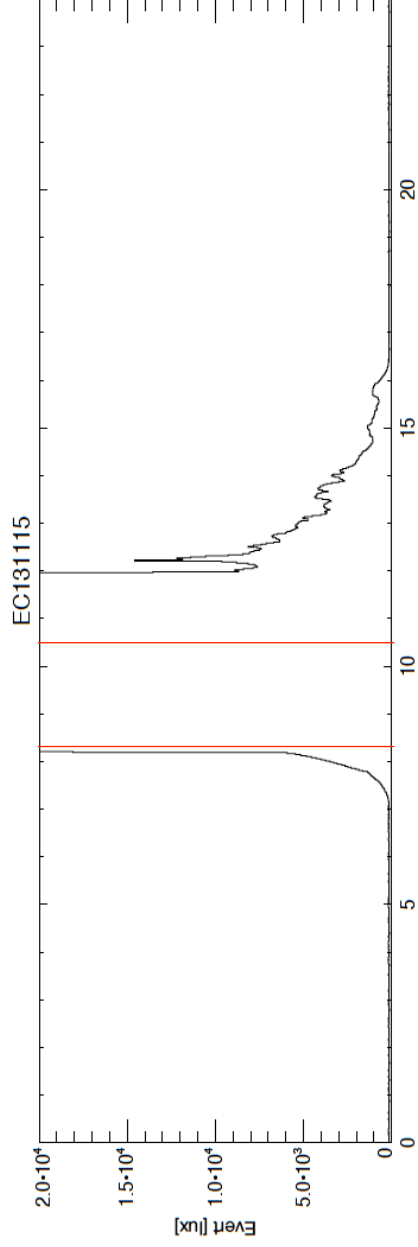
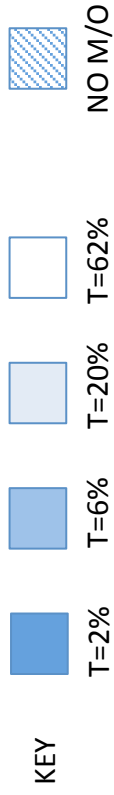
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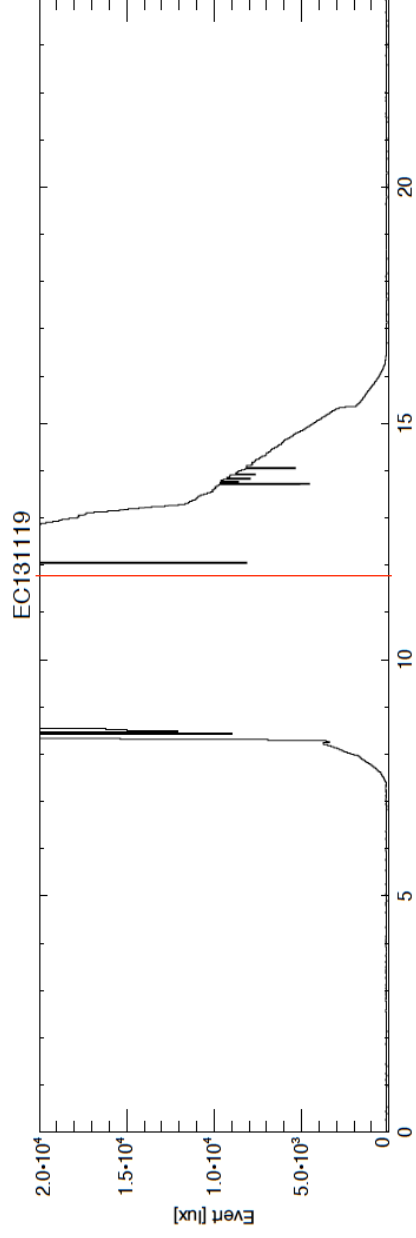
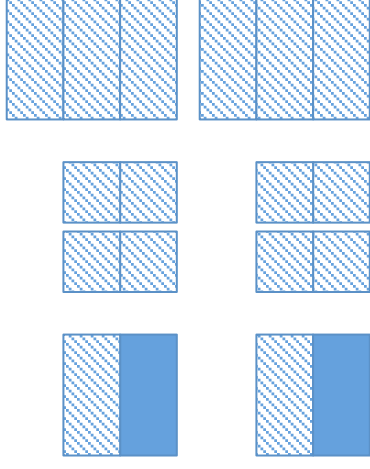
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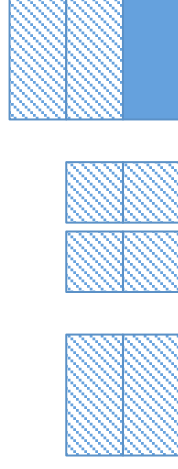


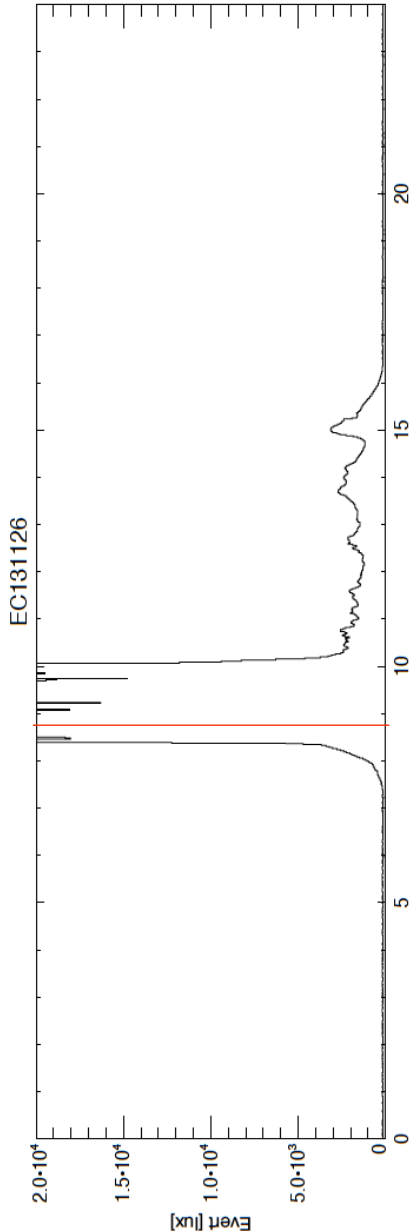
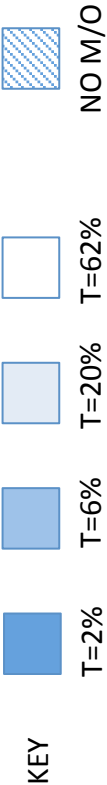
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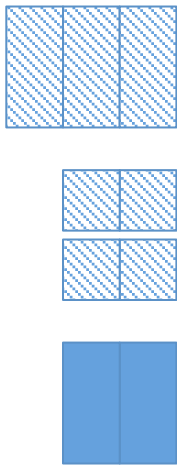


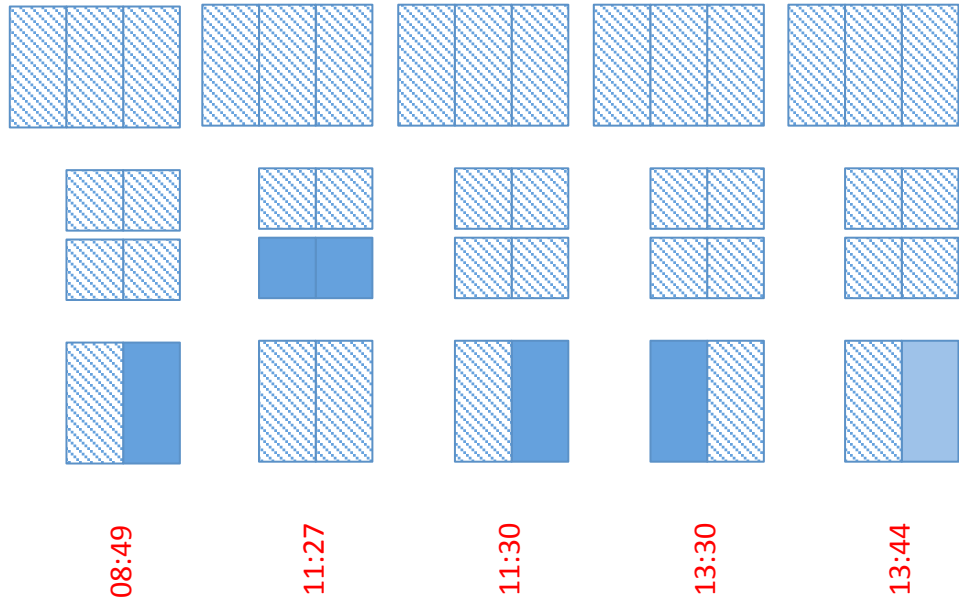
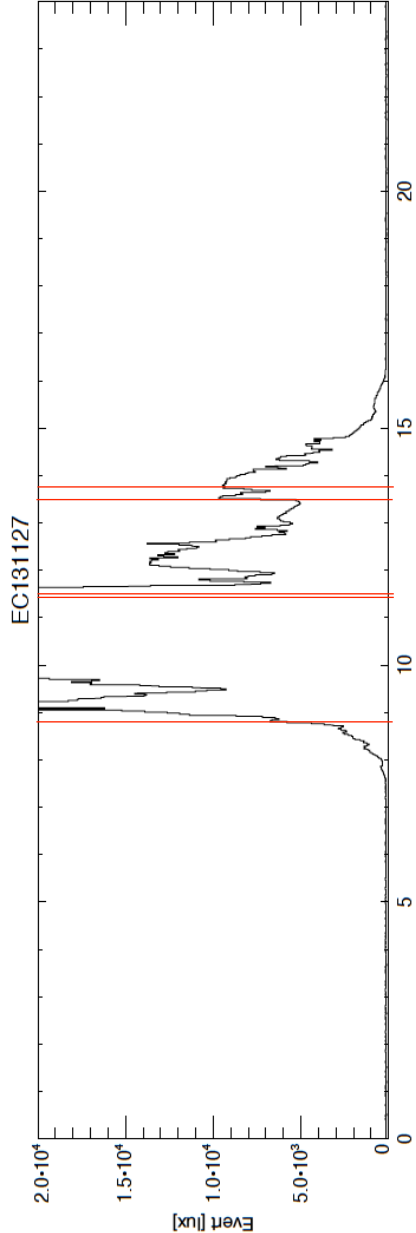
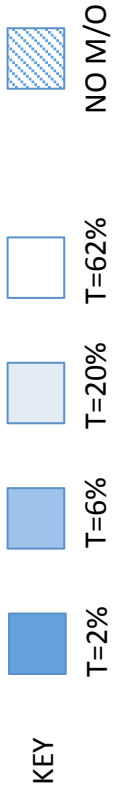
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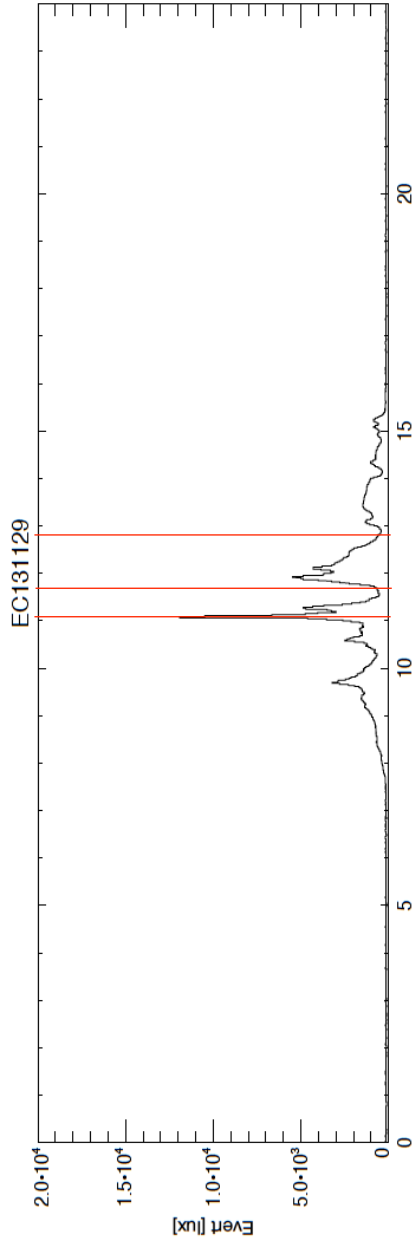
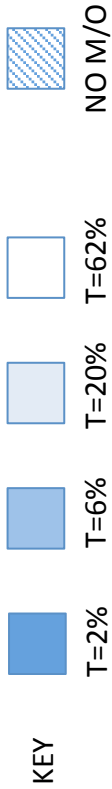




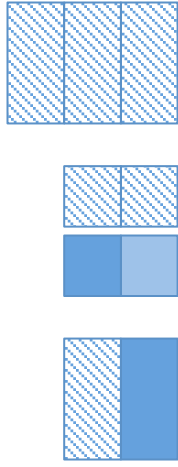
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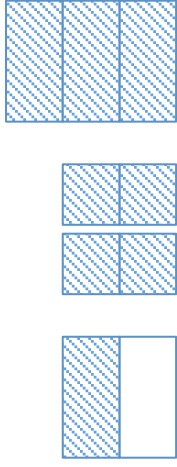




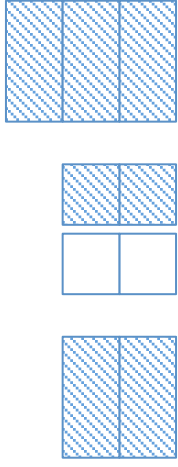
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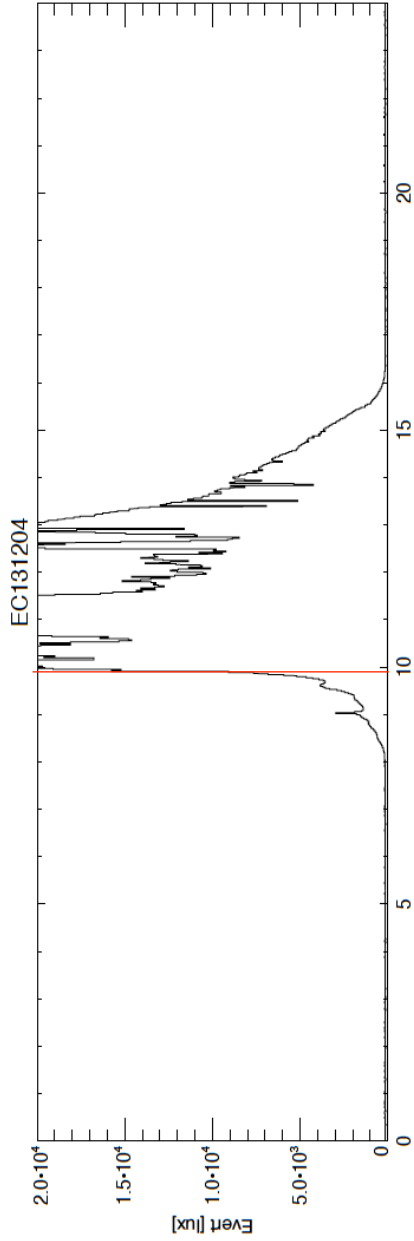
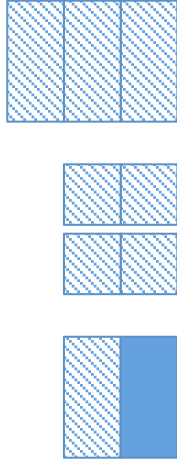
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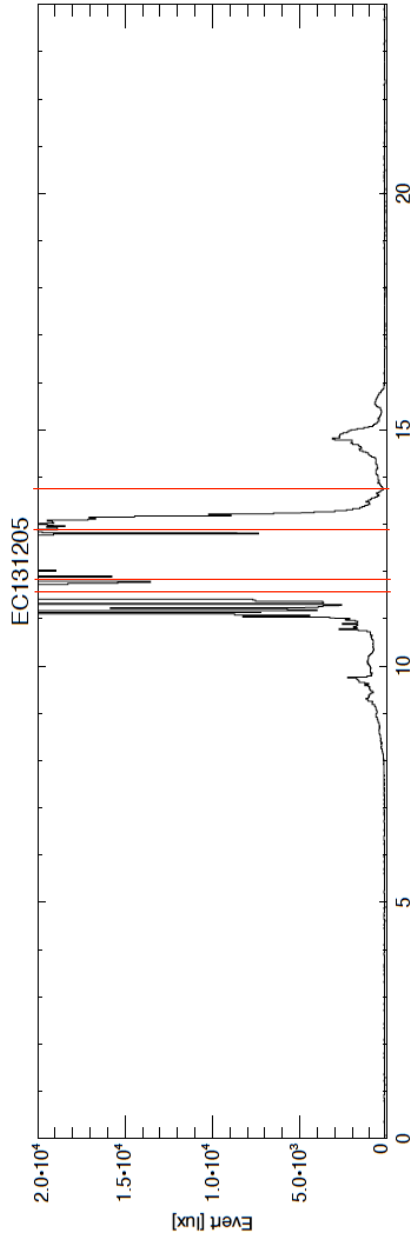
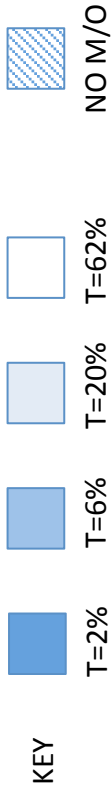


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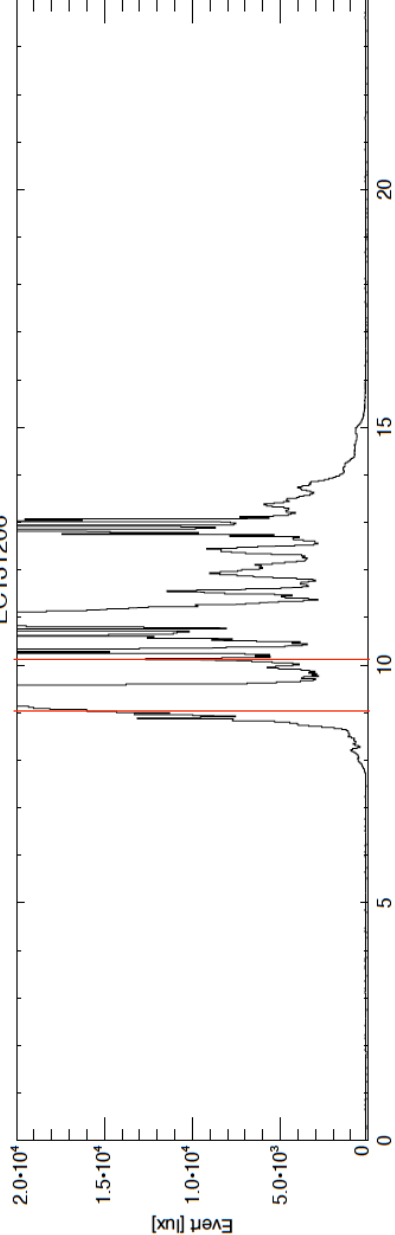
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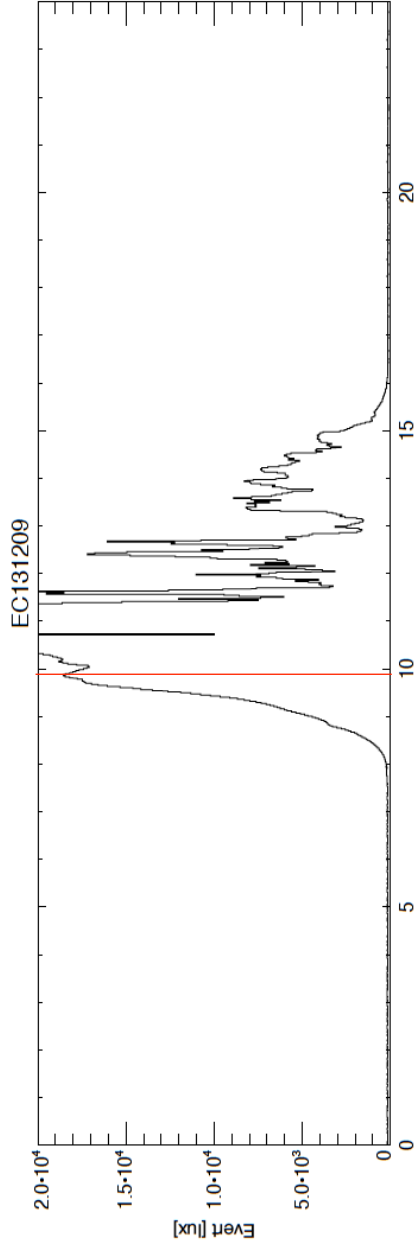
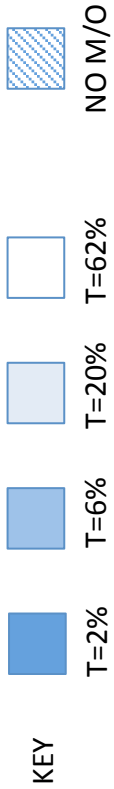
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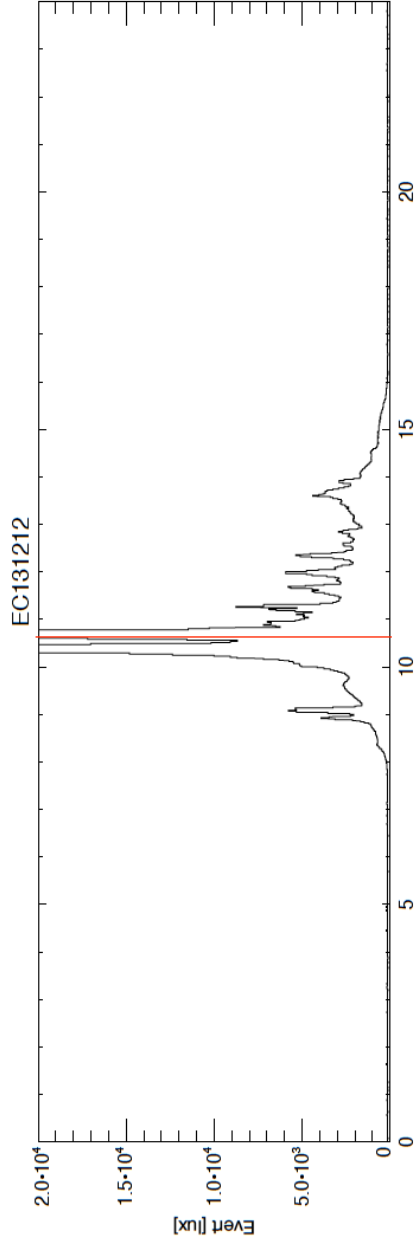
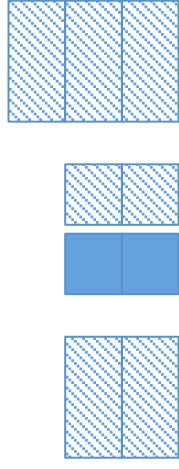


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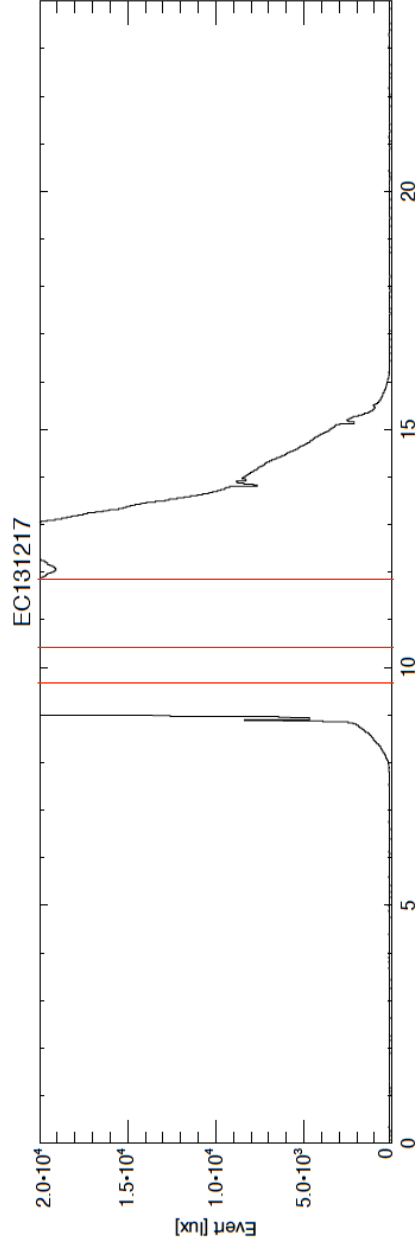
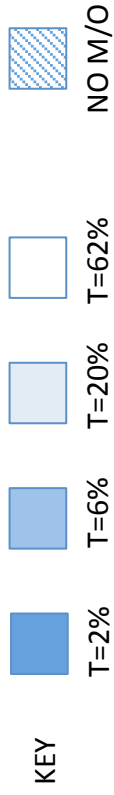
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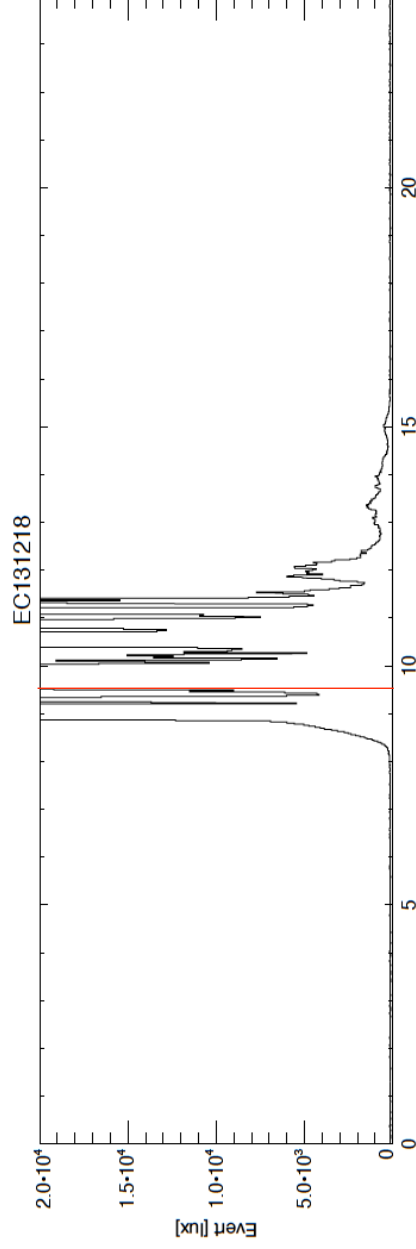
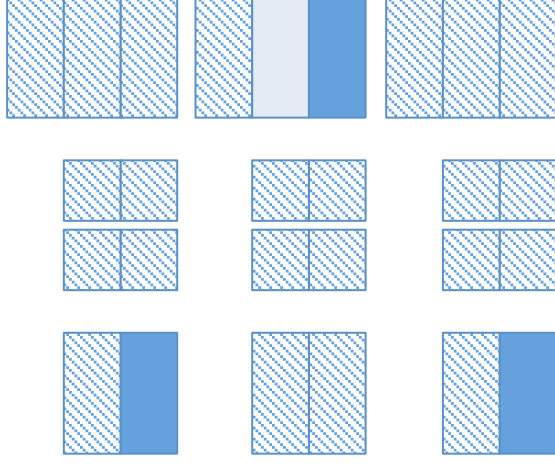




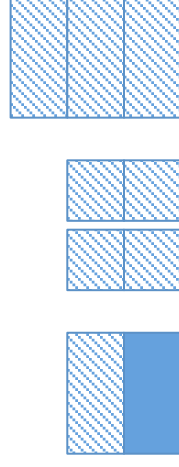
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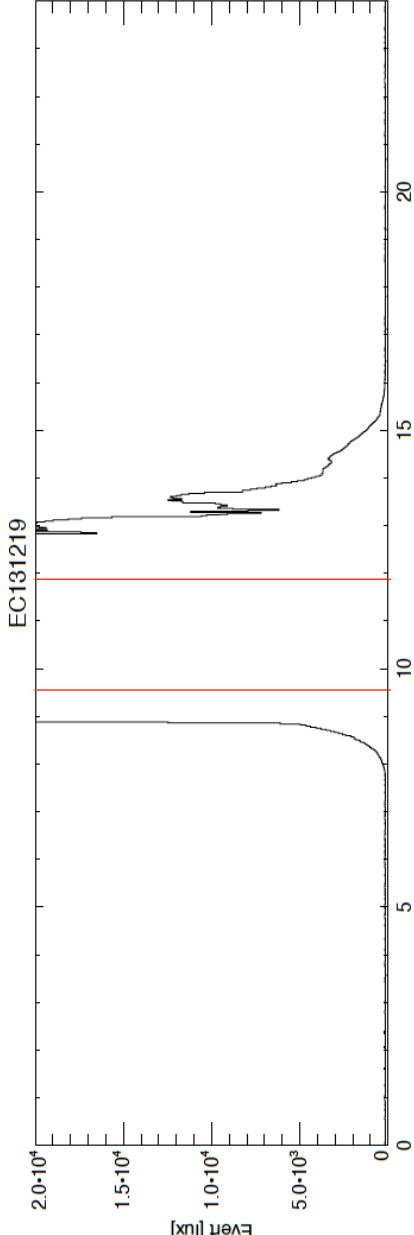
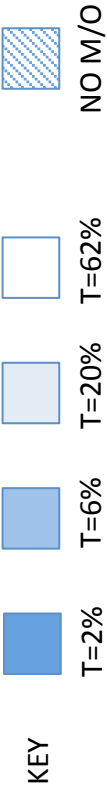
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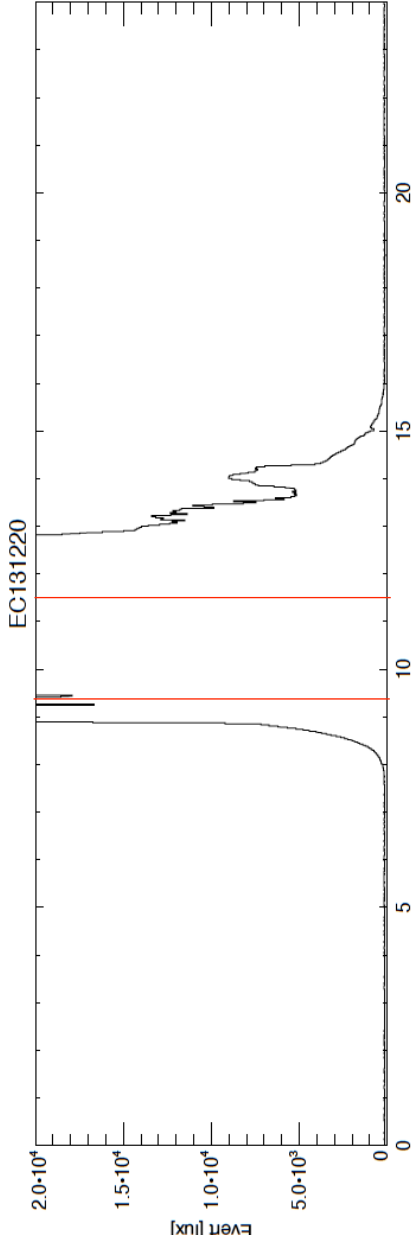
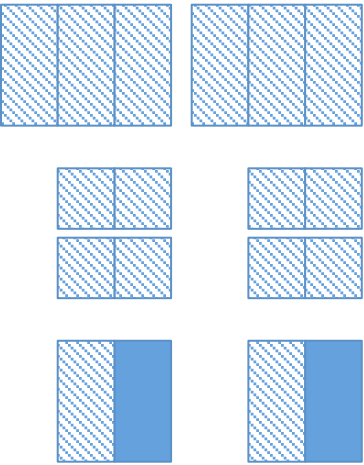
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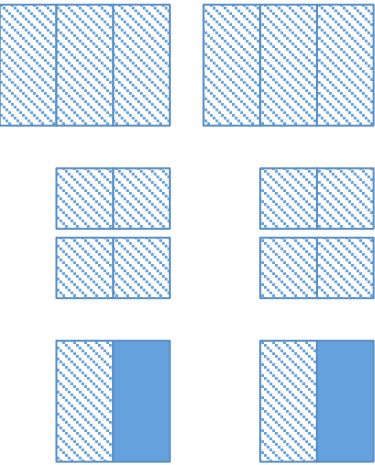
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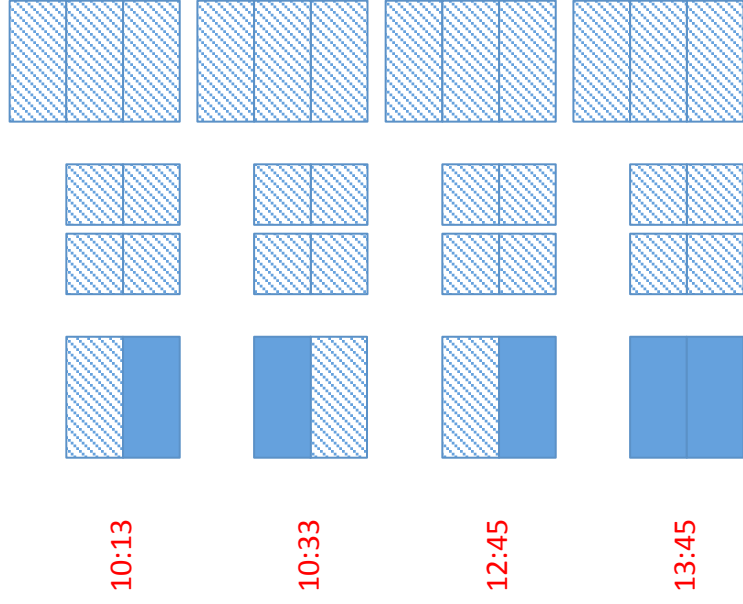
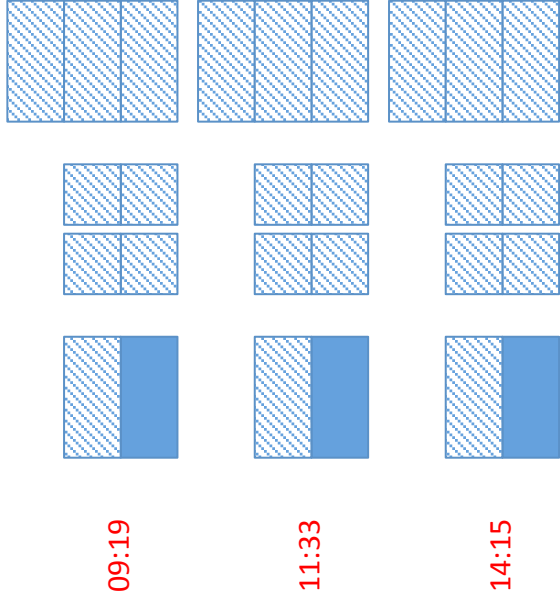
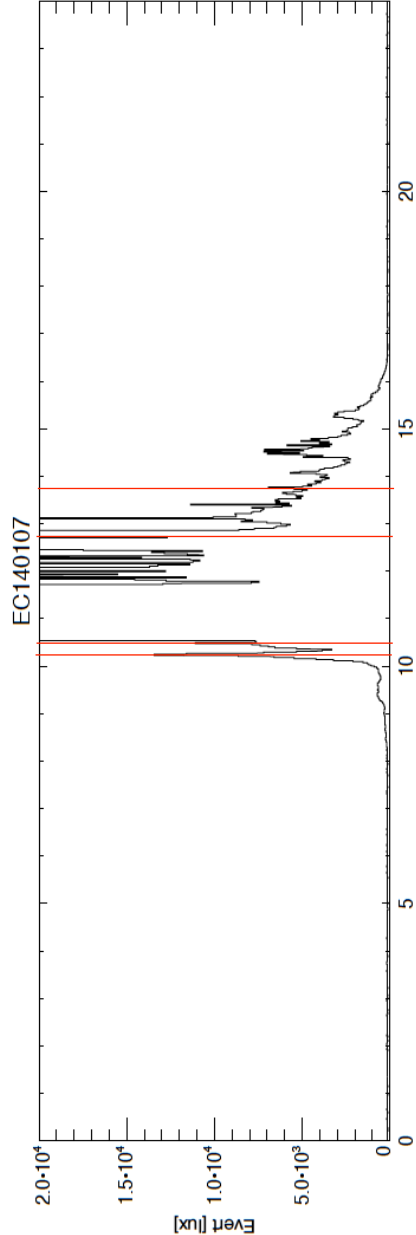
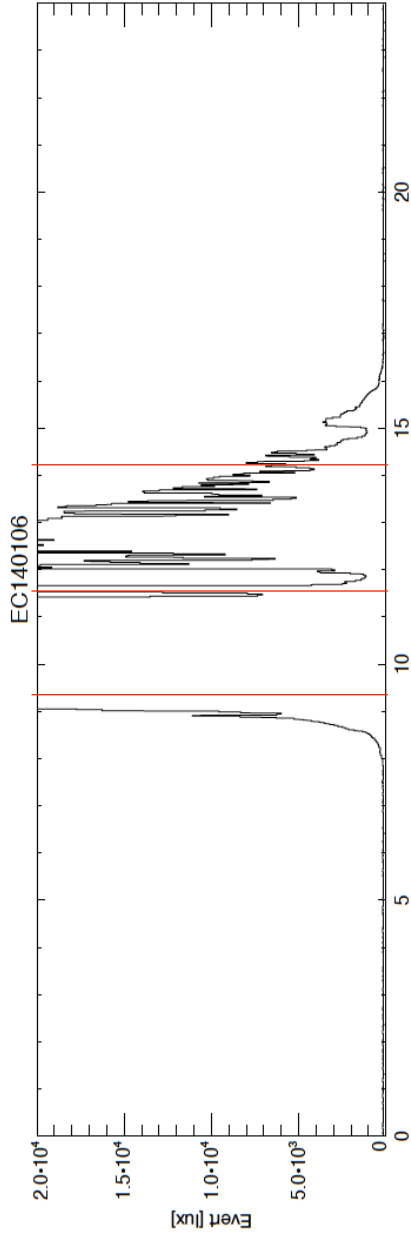
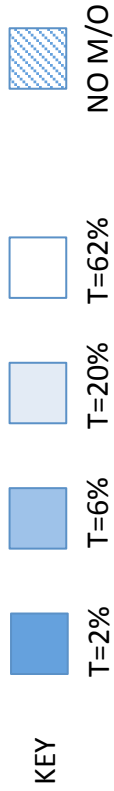
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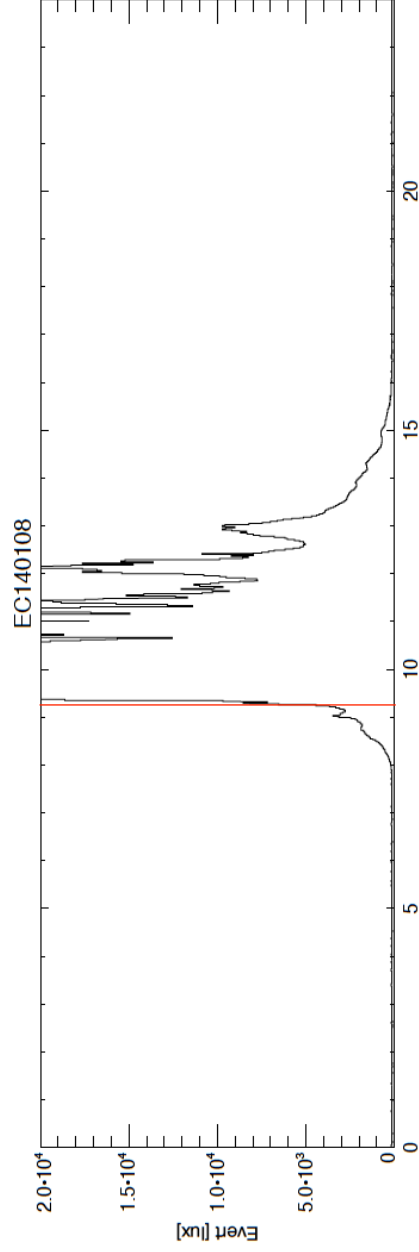
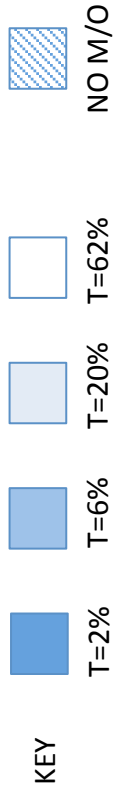


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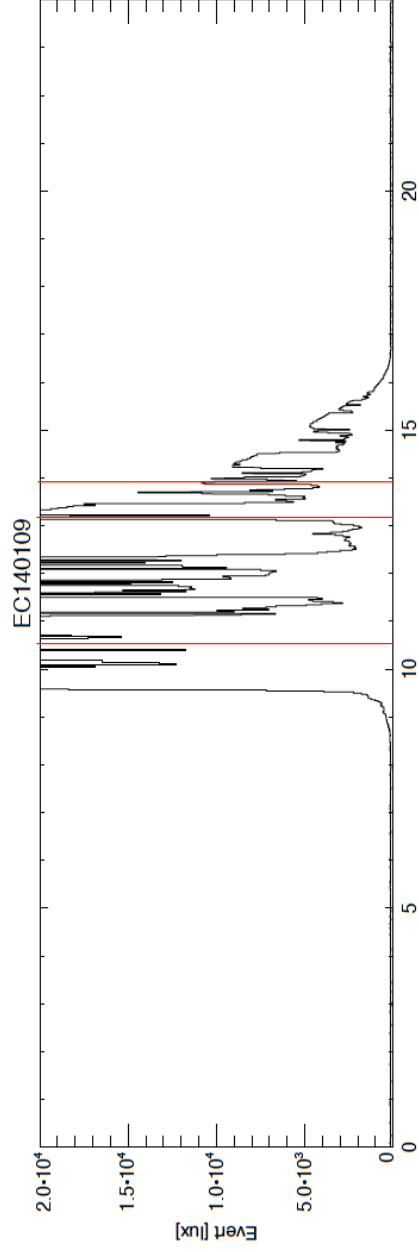
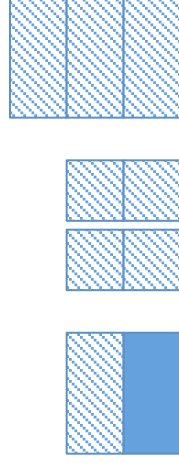
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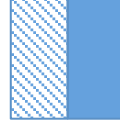
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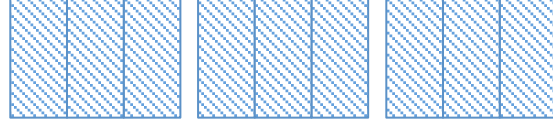
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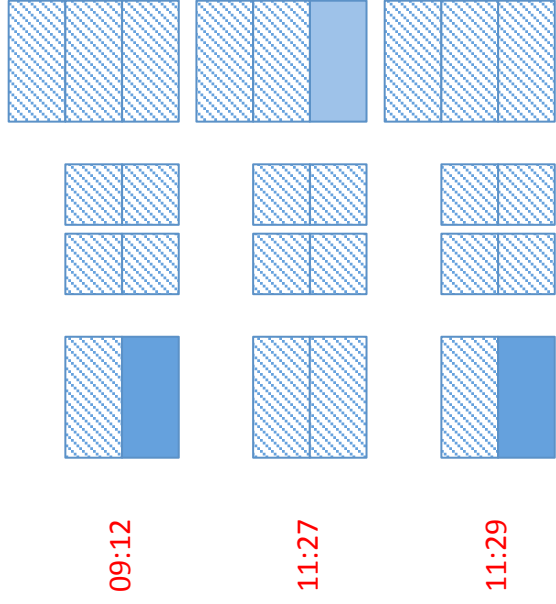
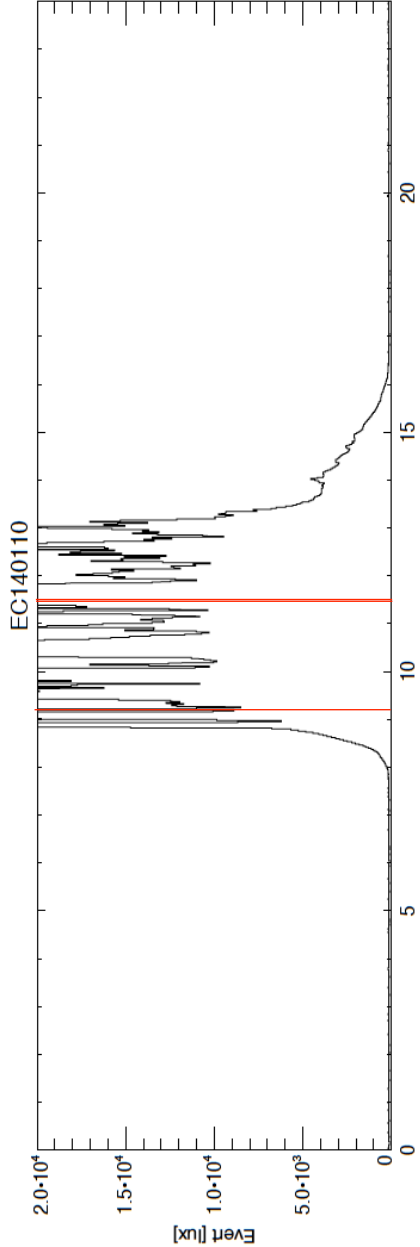
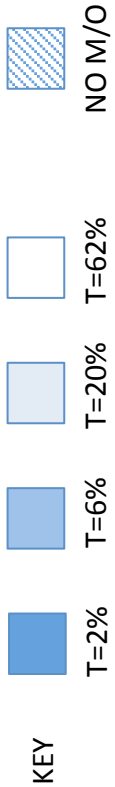


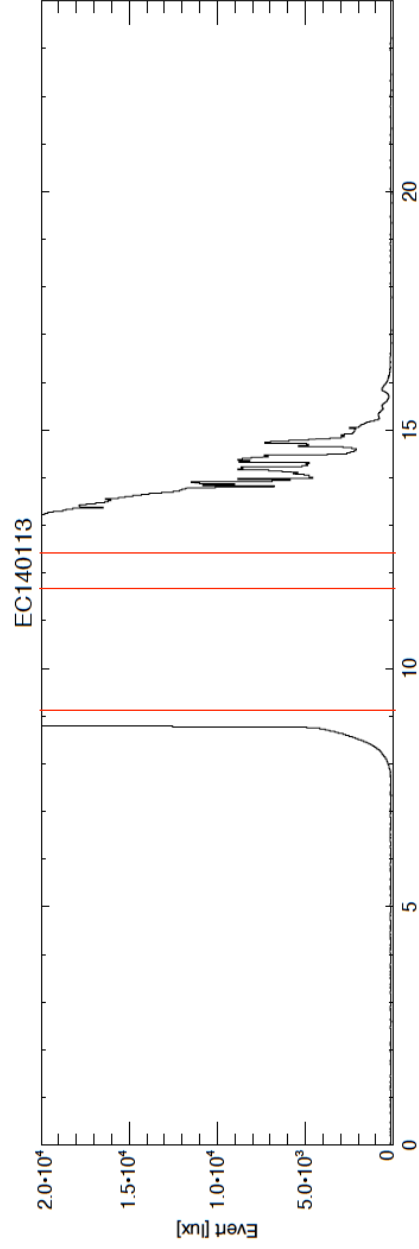
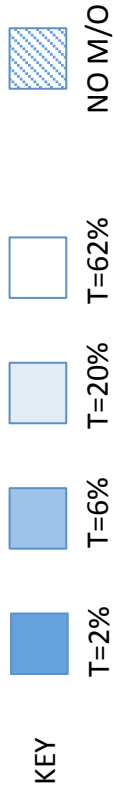
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13:54



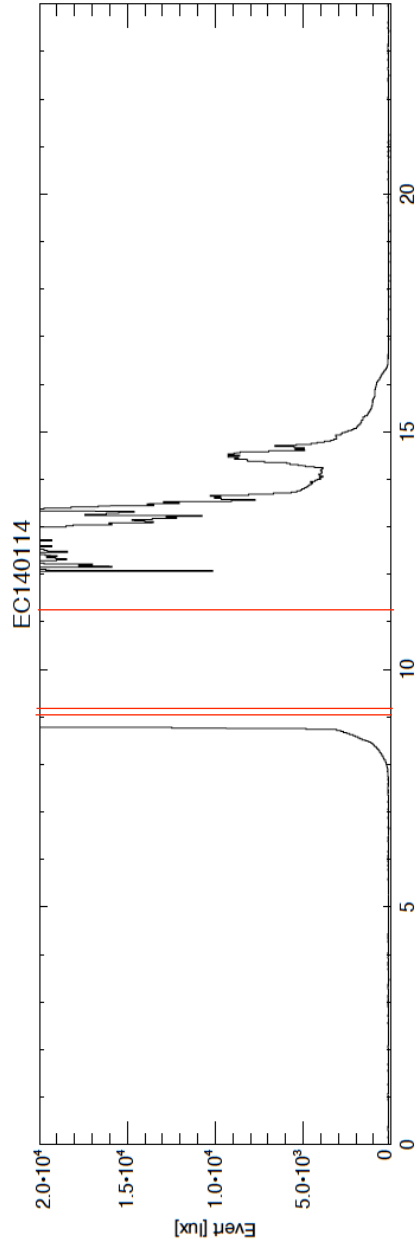
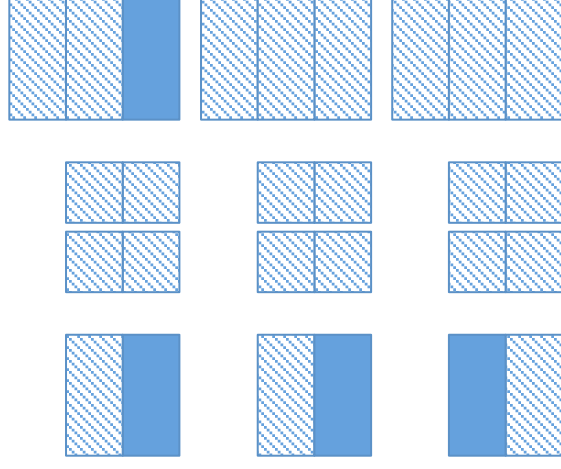




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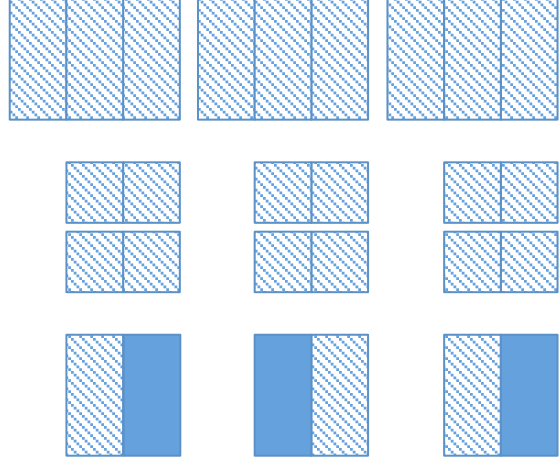
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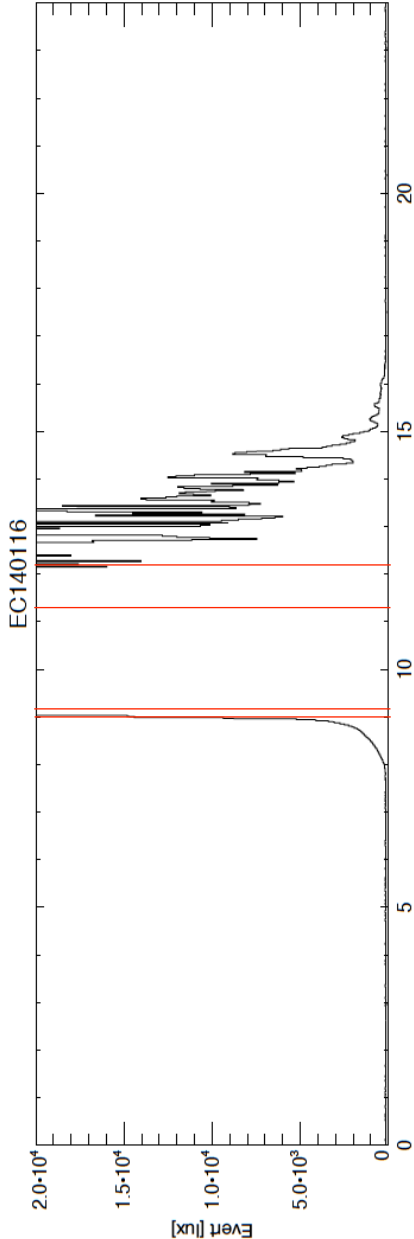
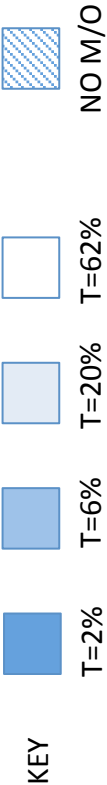


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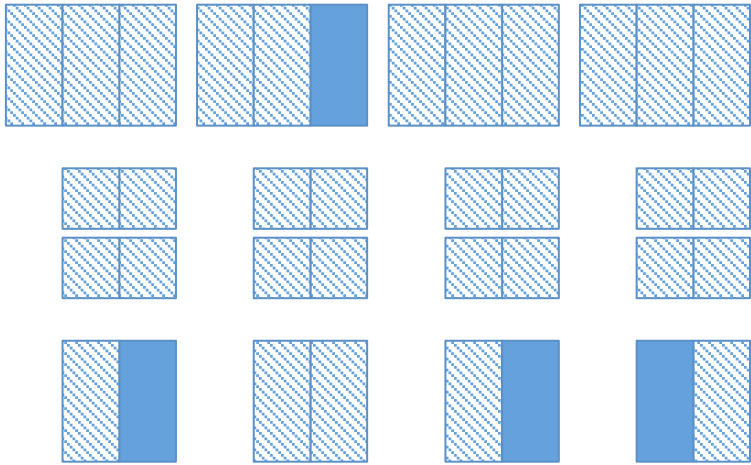


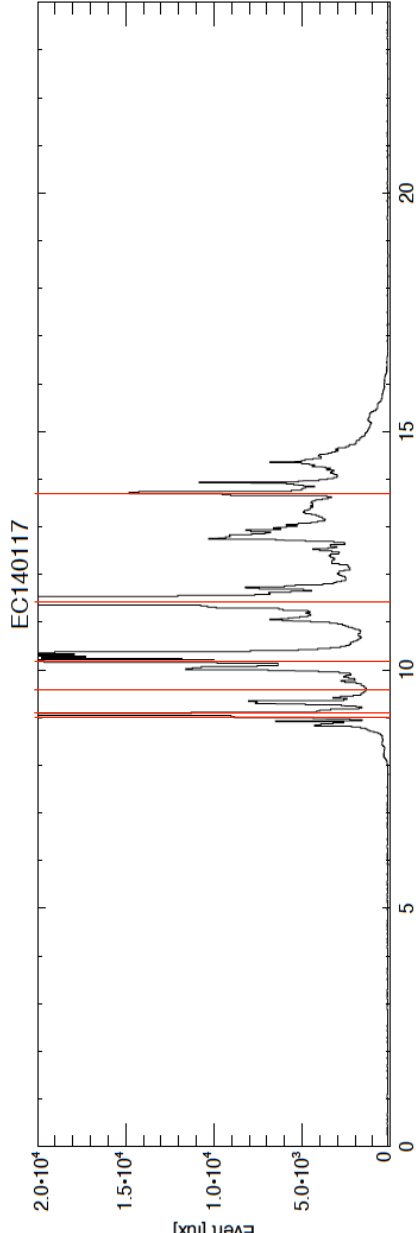
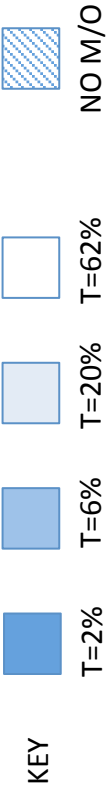
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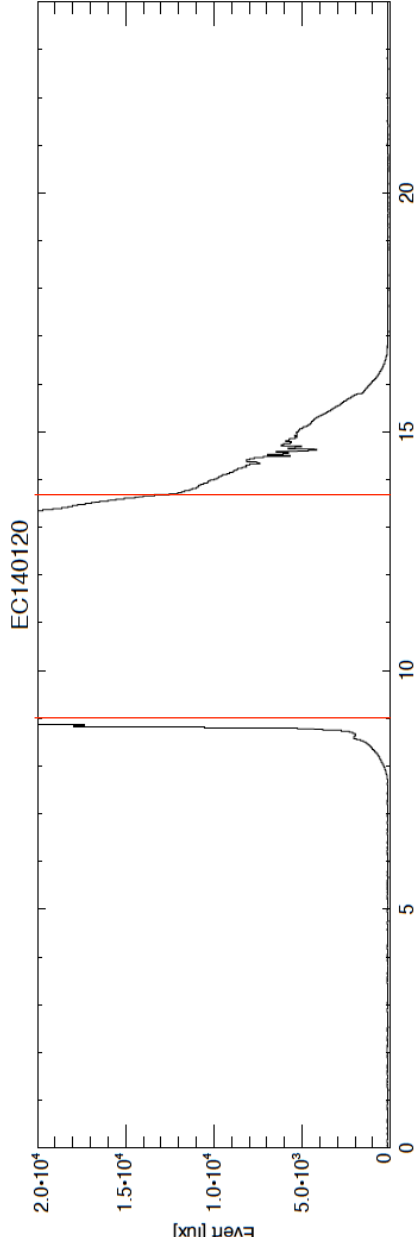
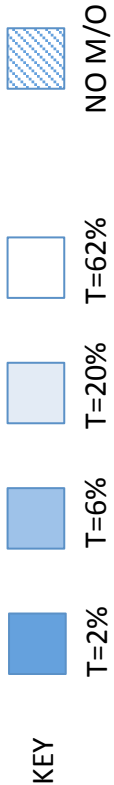
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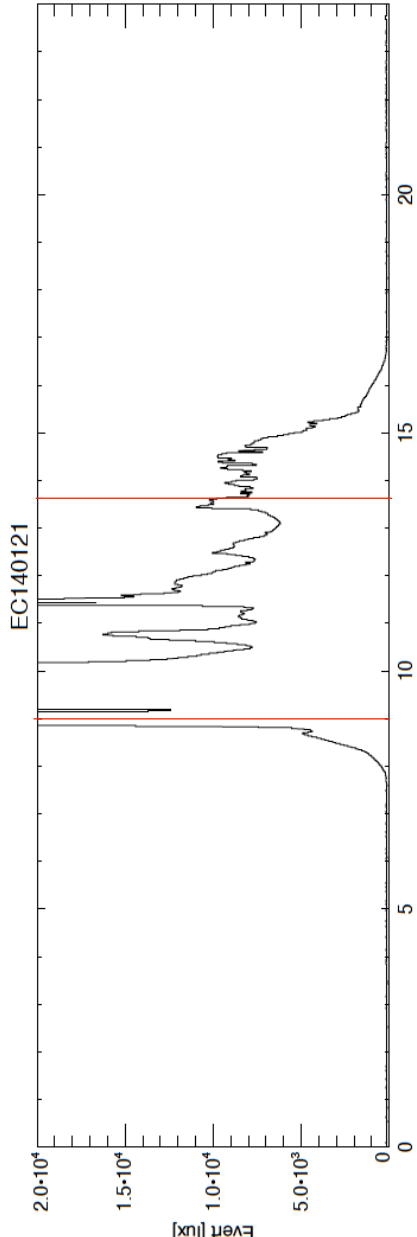
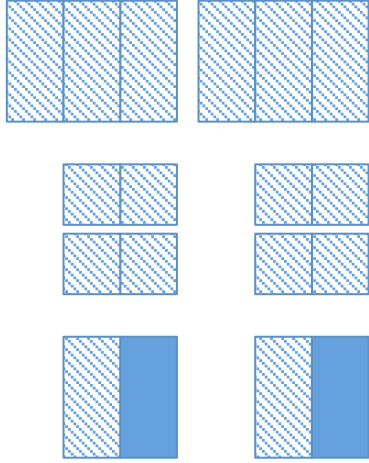
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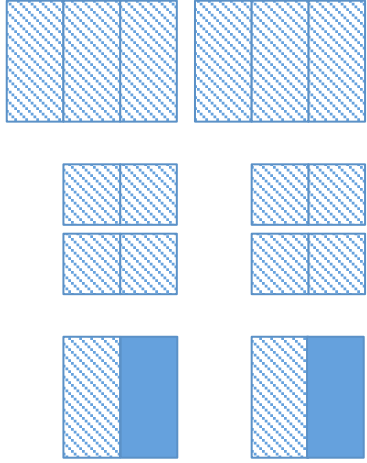
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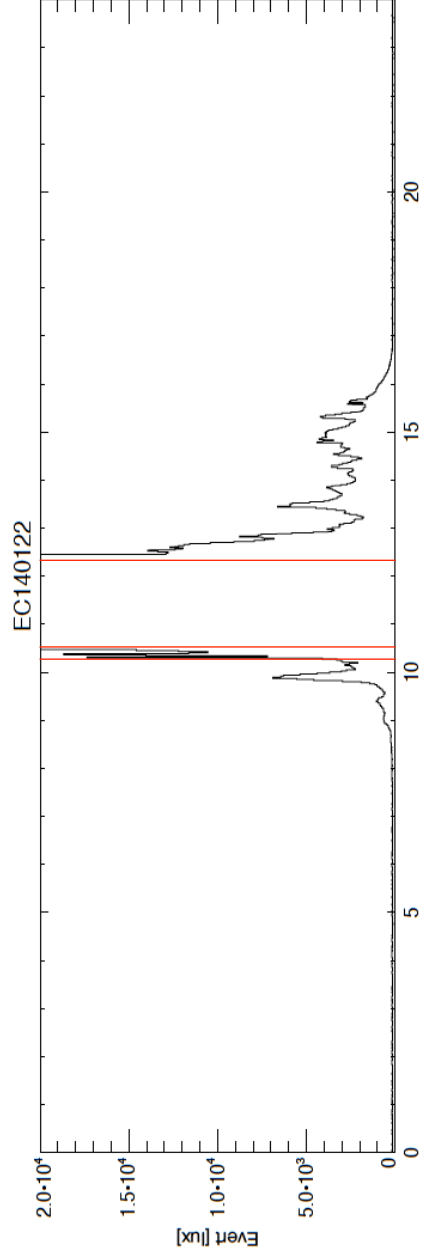
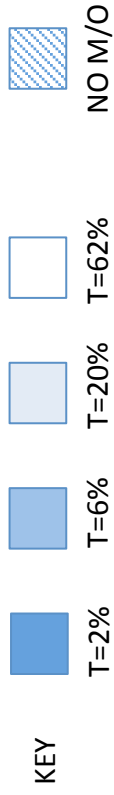
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13:36

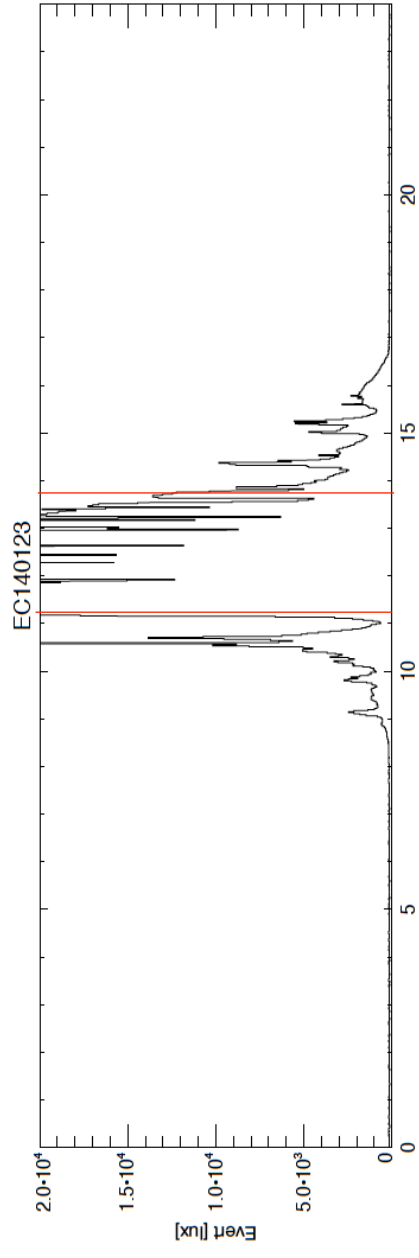
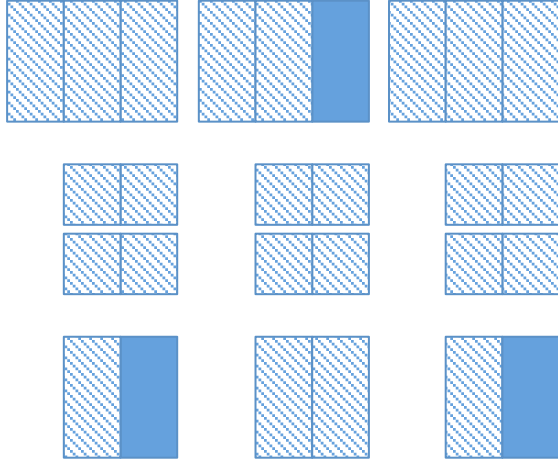




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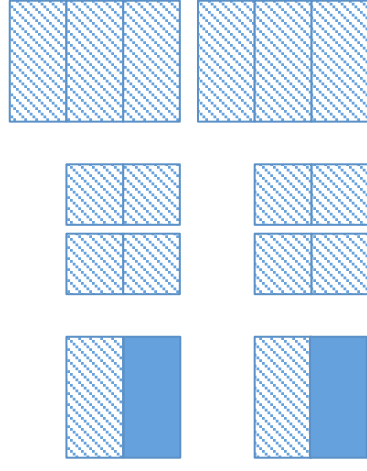
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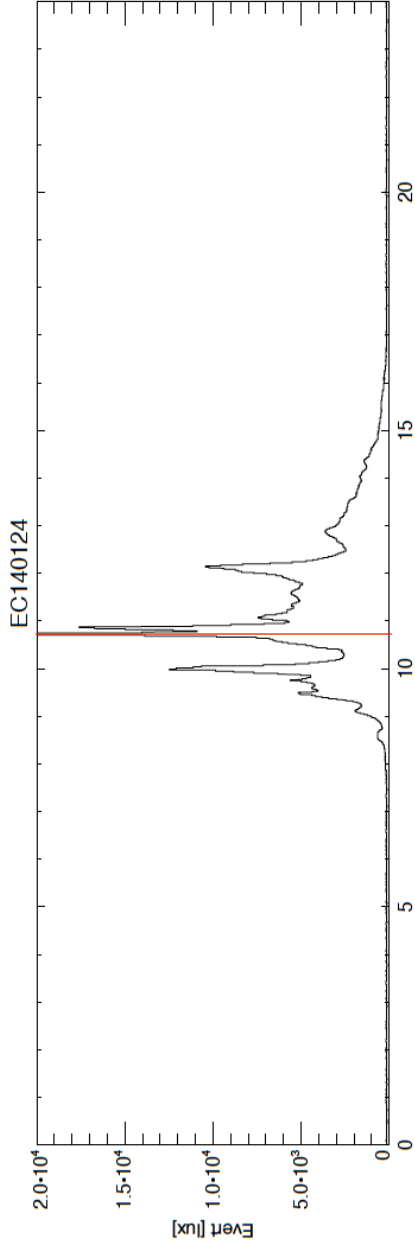
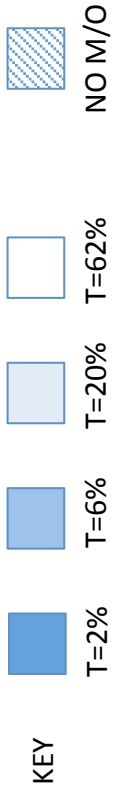
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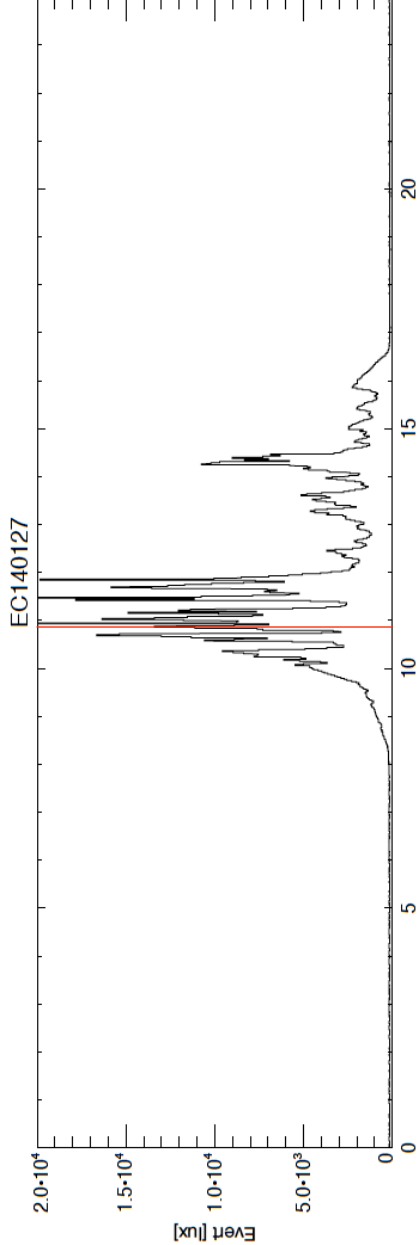
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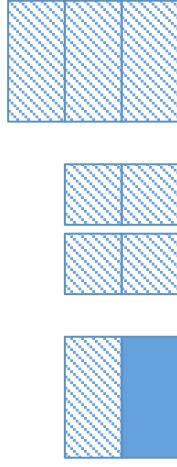


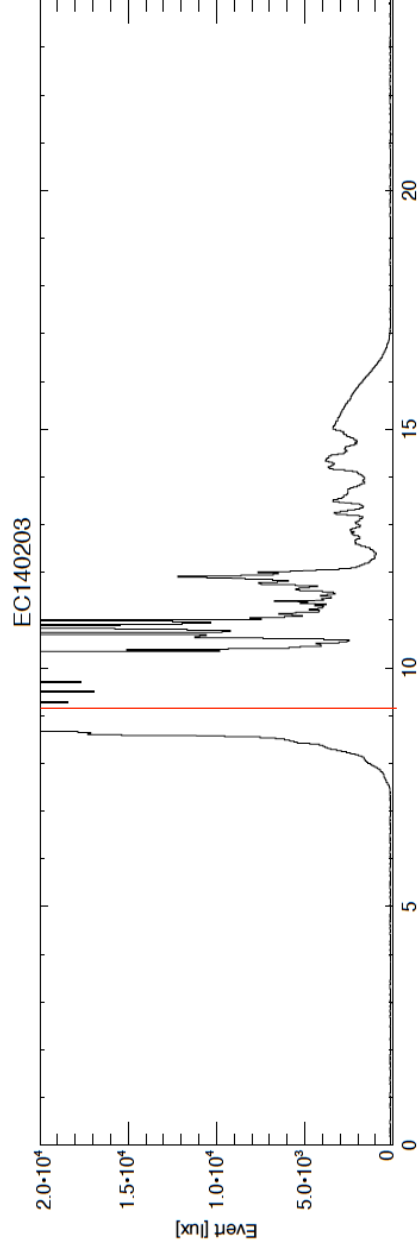
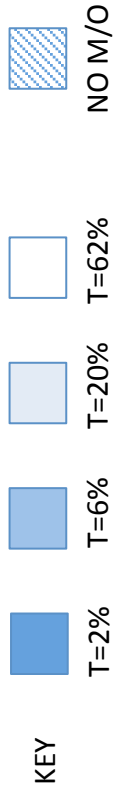


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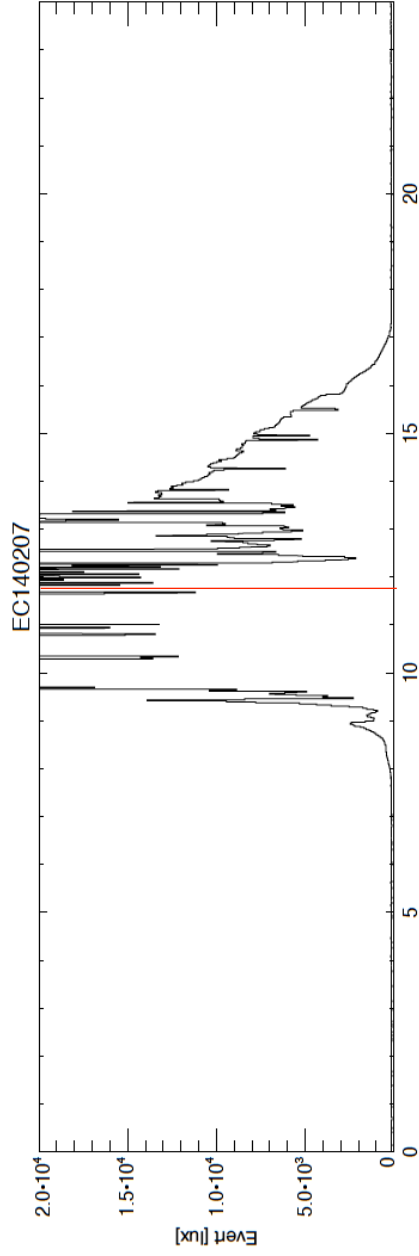
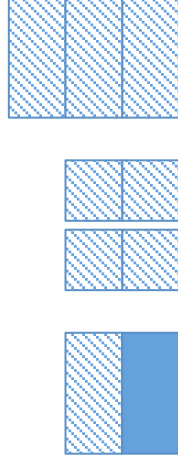


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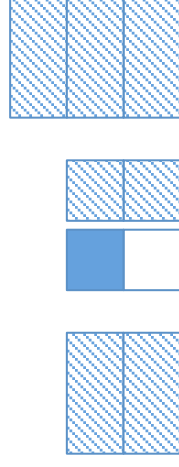


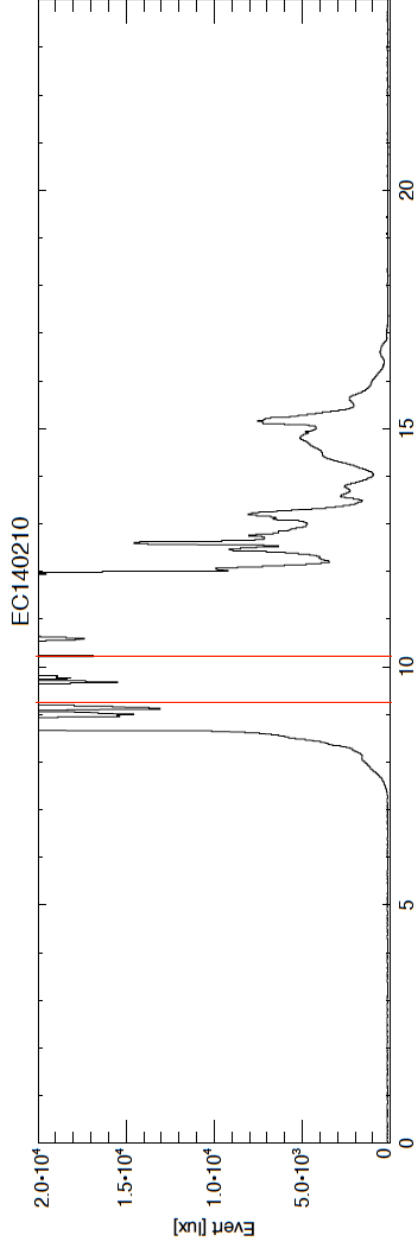
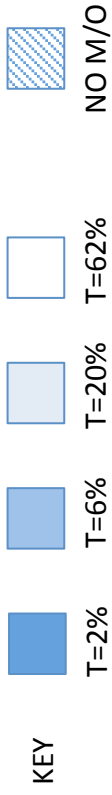


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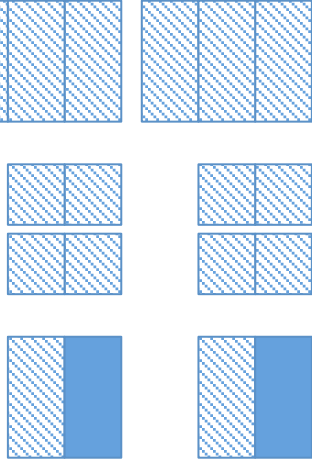


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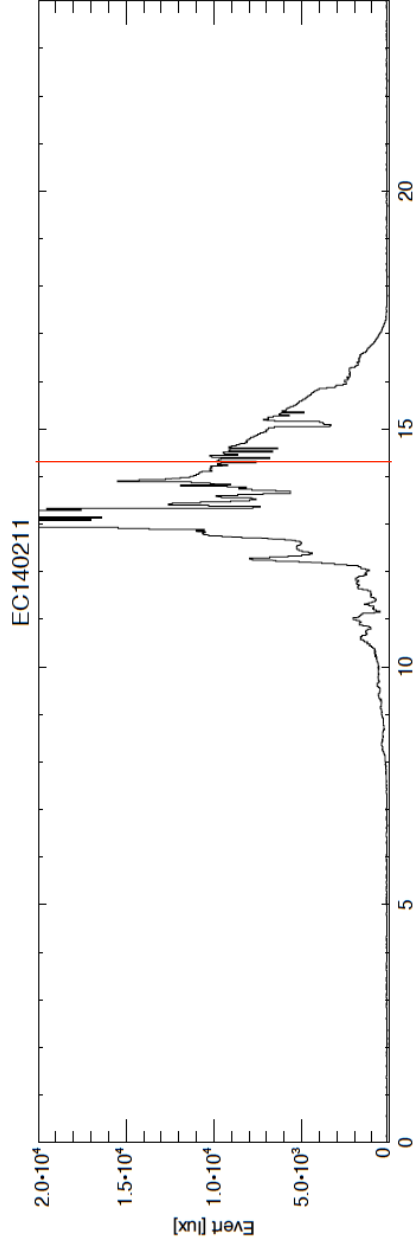




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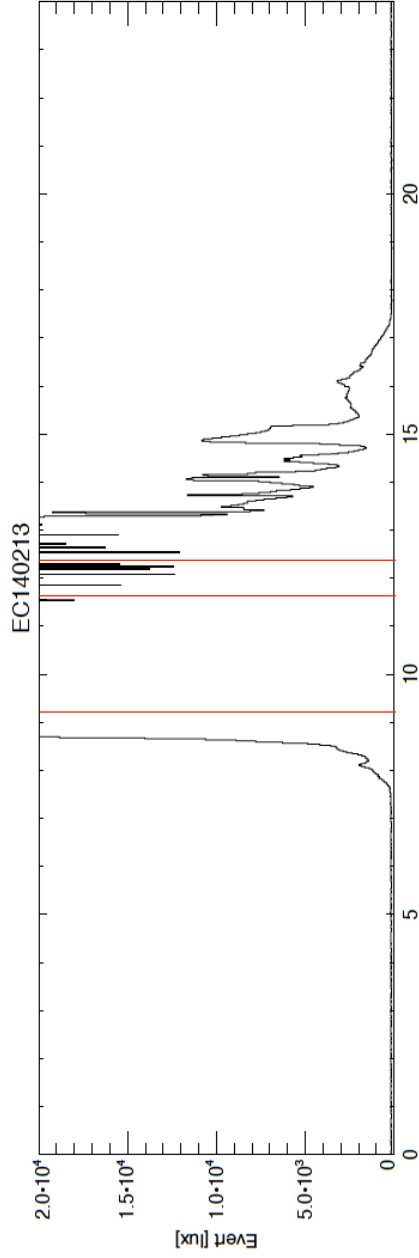
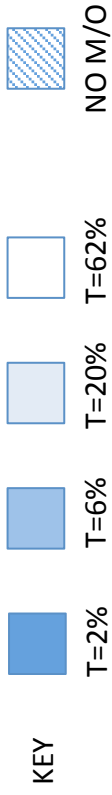


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14:19

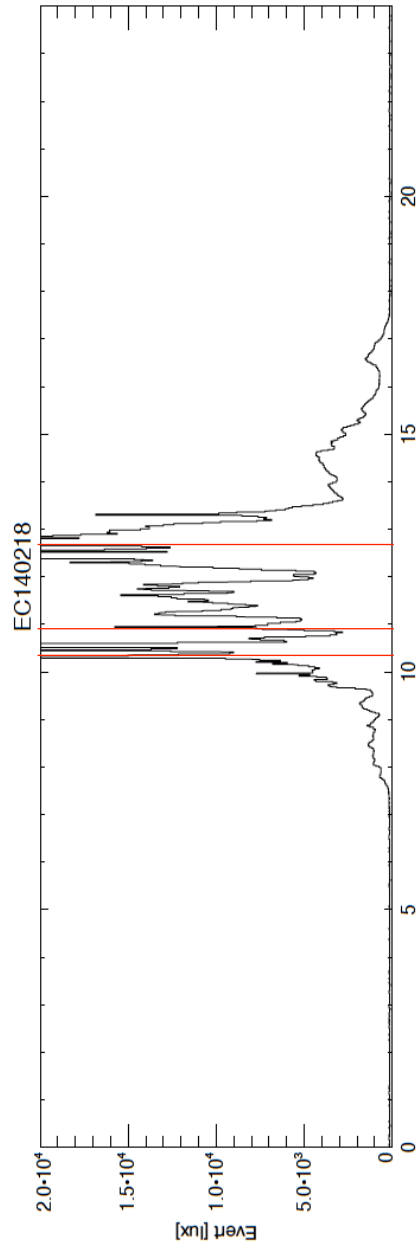
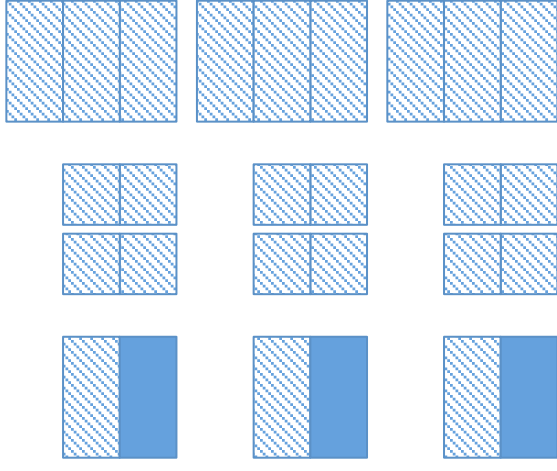




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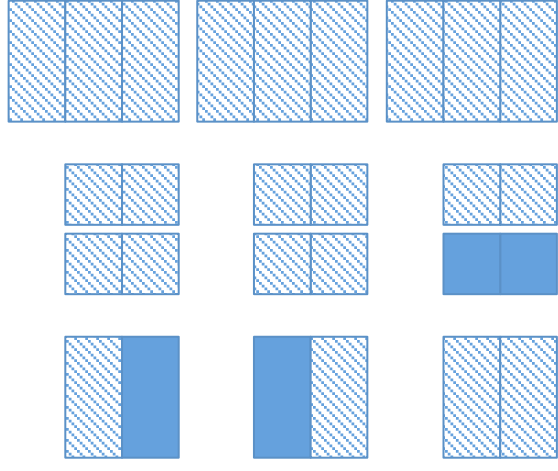
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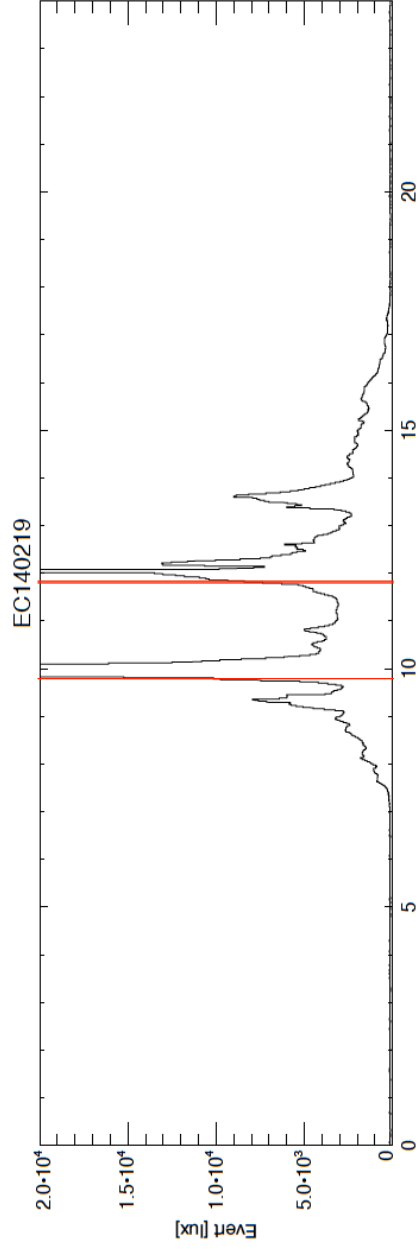
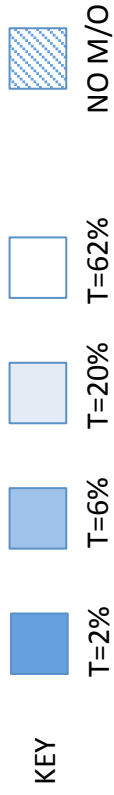


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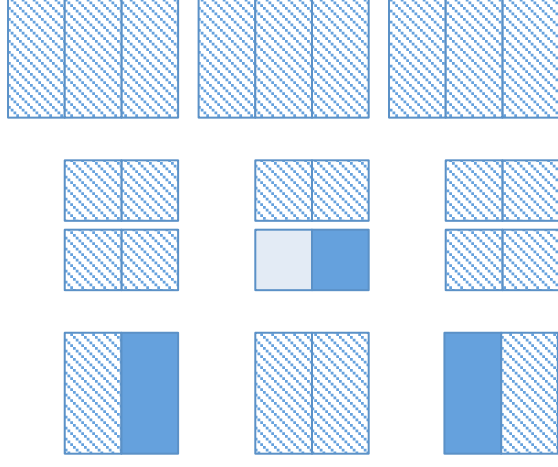
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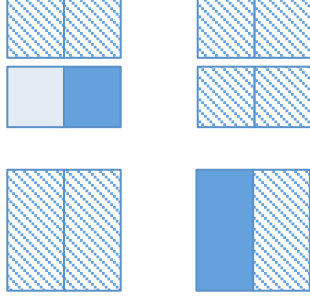




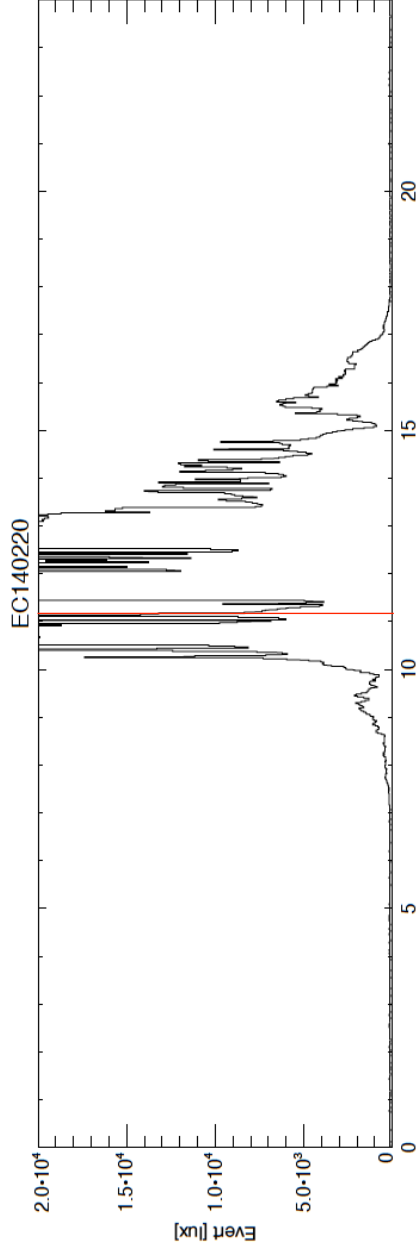
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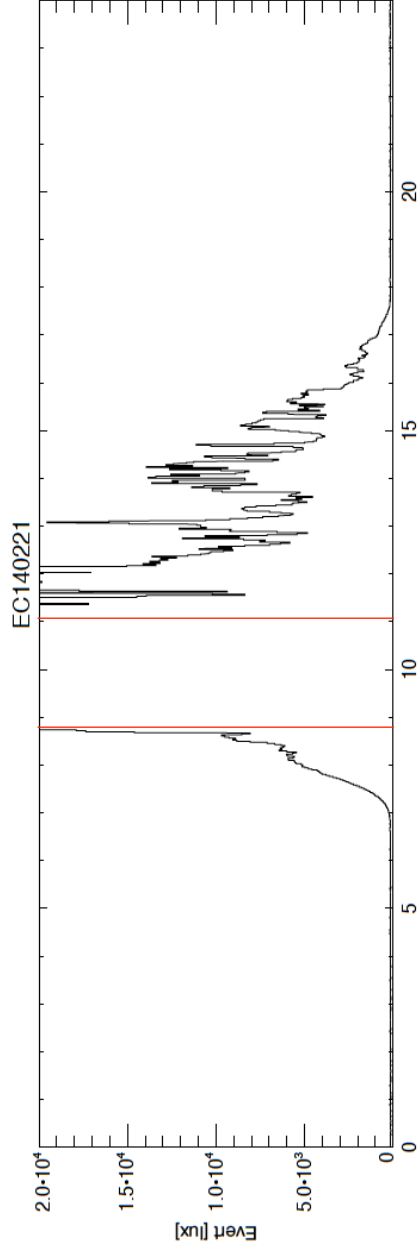
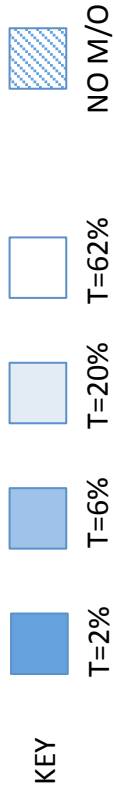


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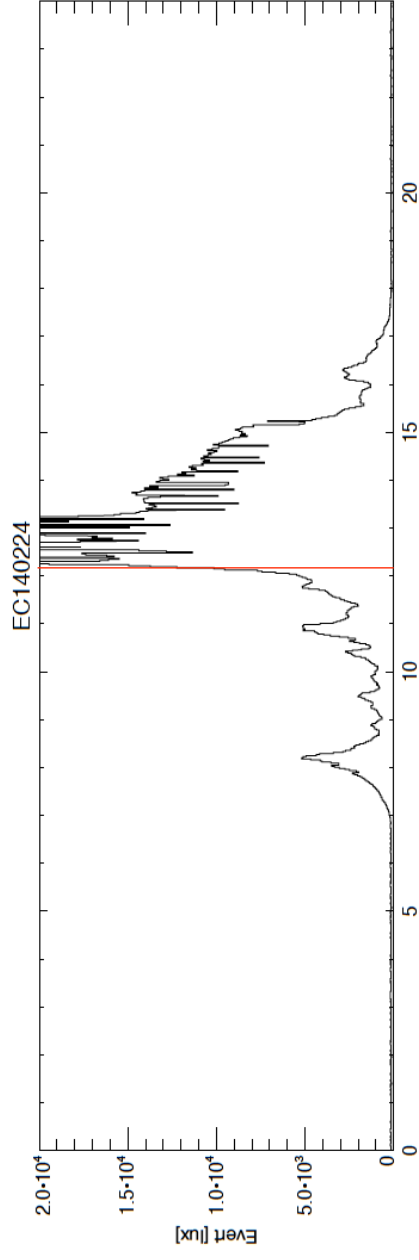
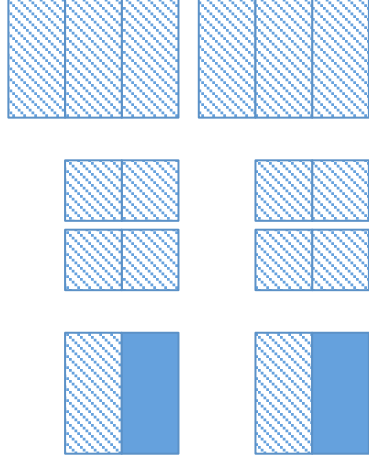
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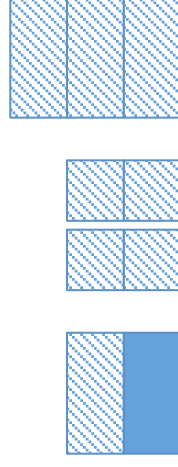


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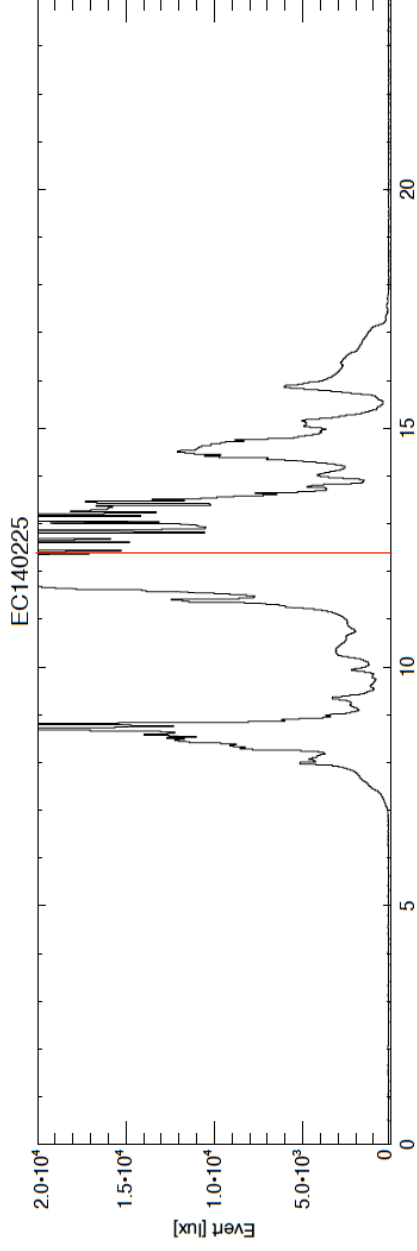
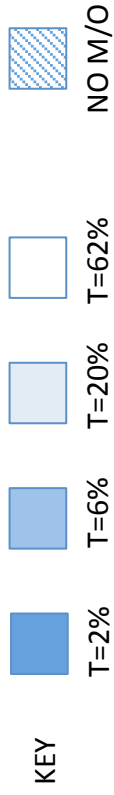
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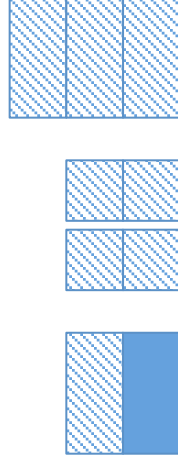




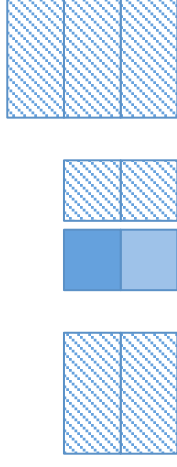
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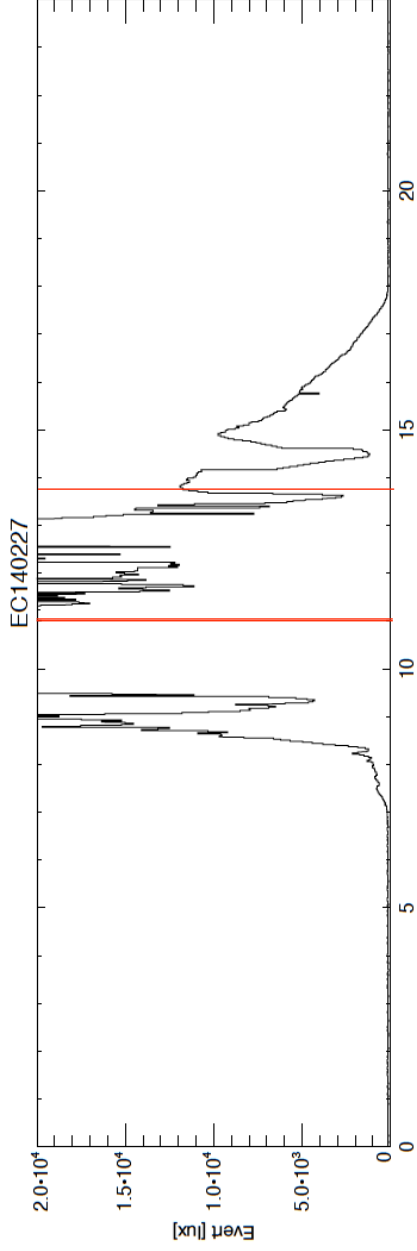
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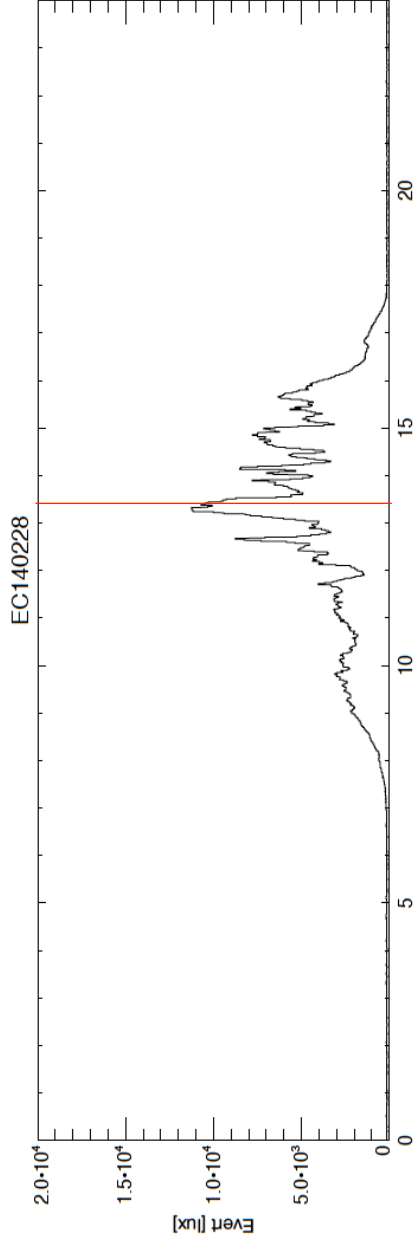
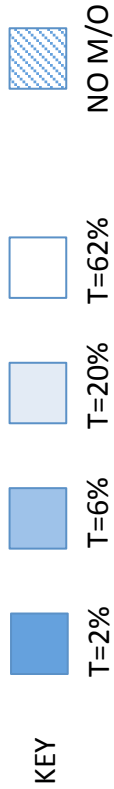


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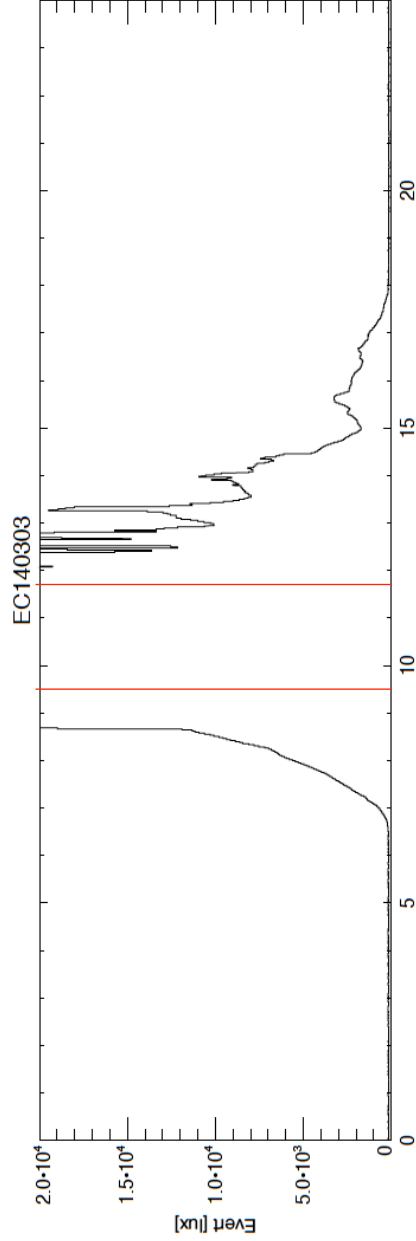
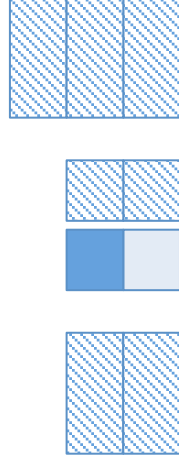


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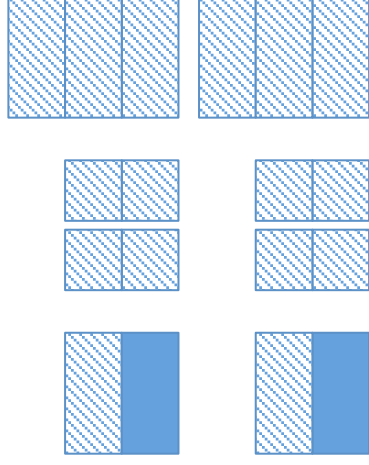




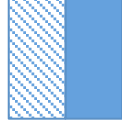
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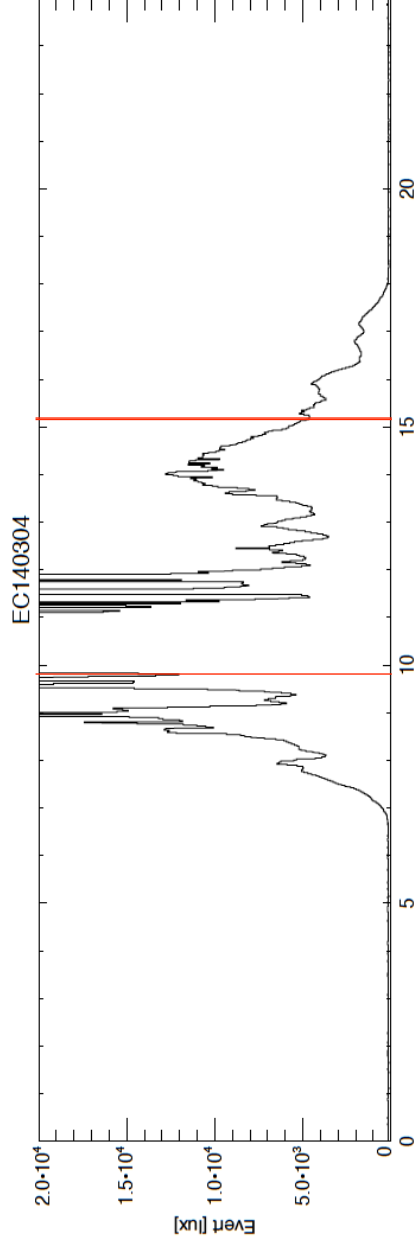
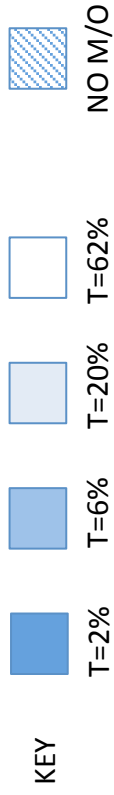


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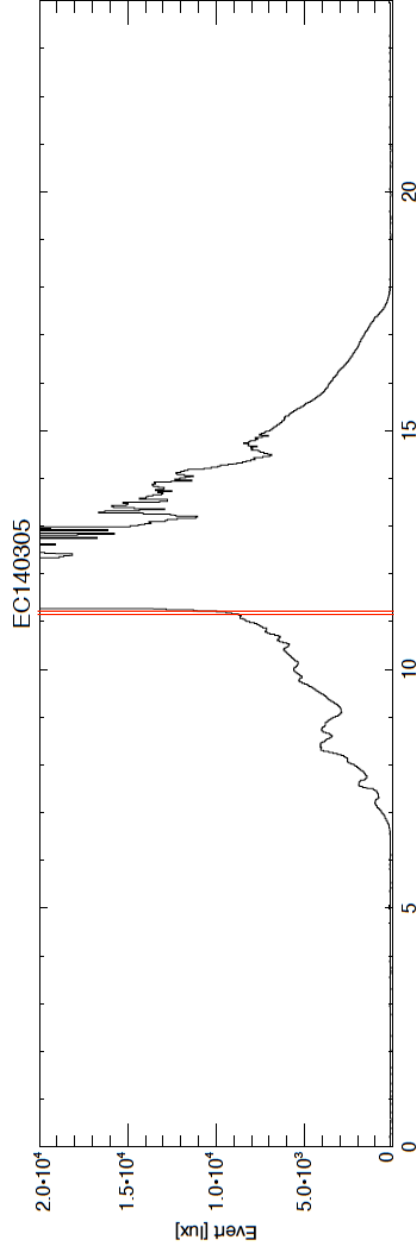




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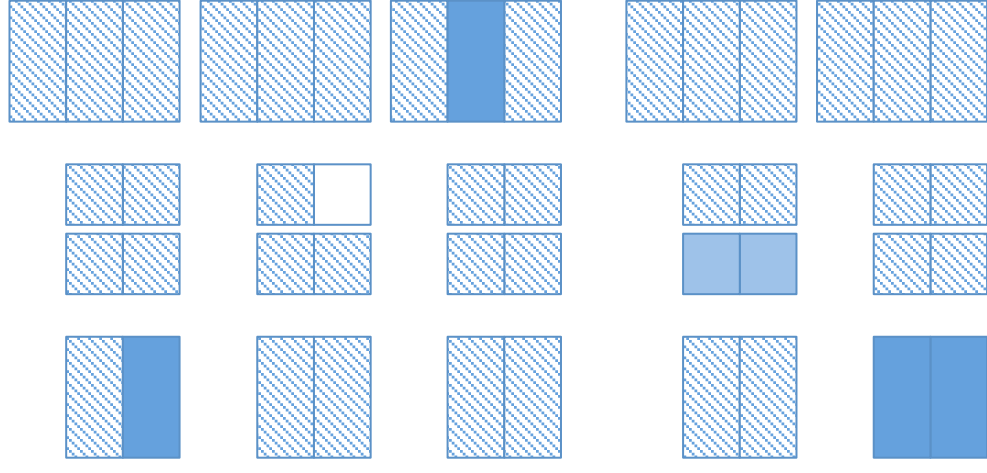
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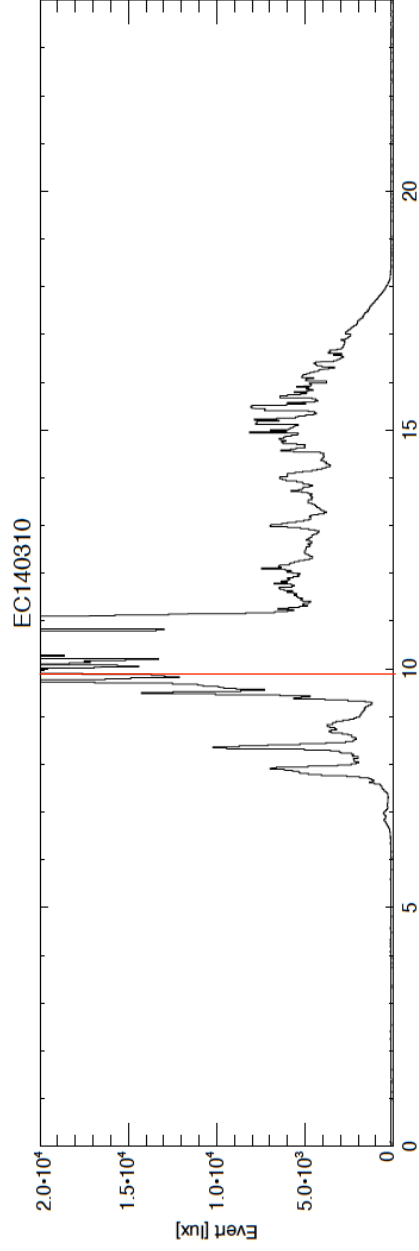
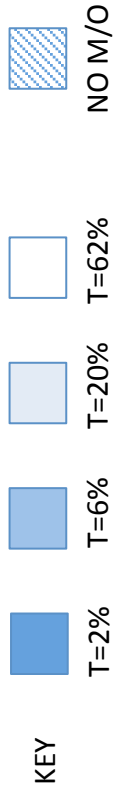
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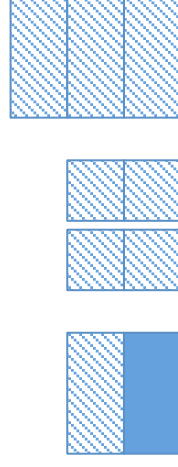
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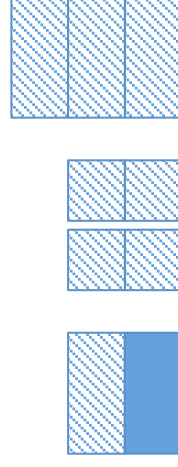




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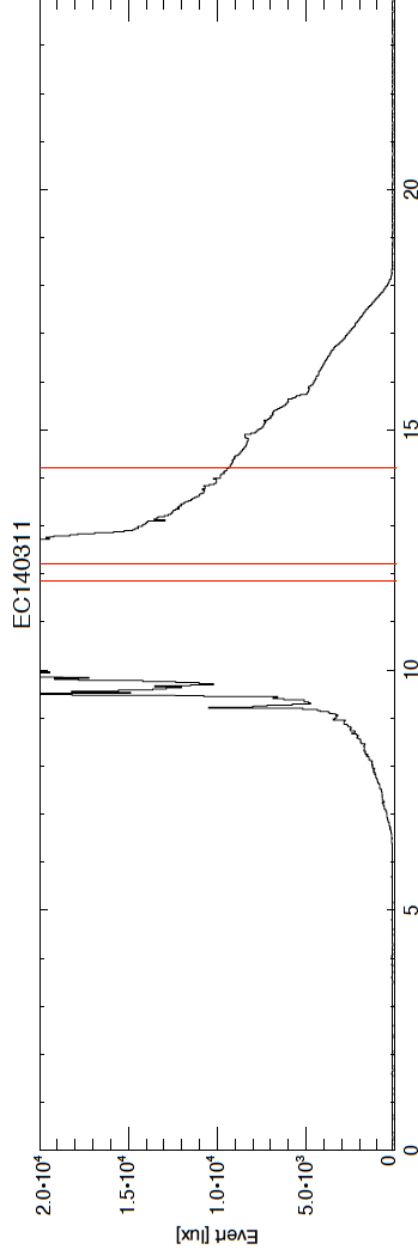
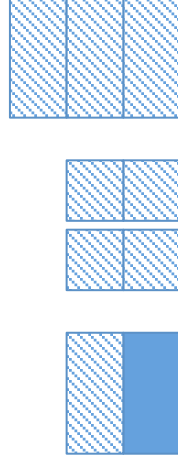
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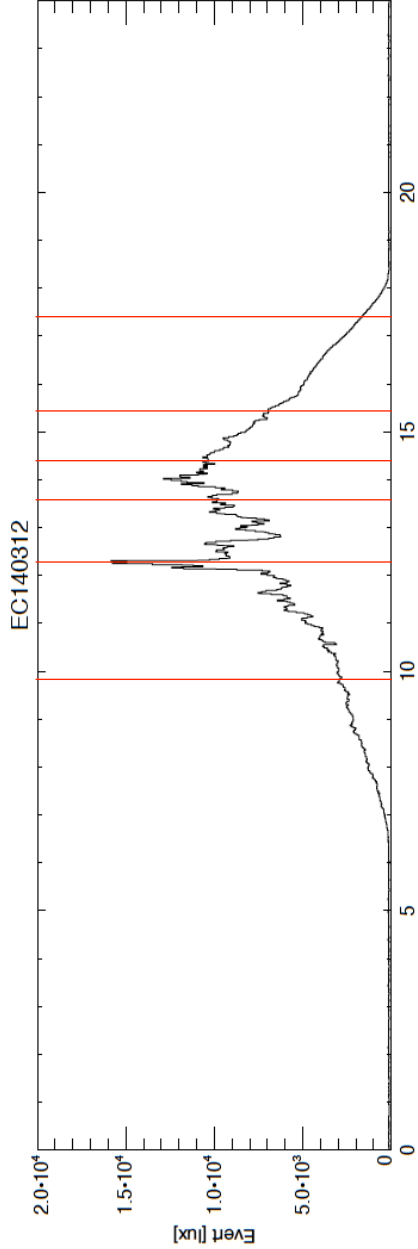
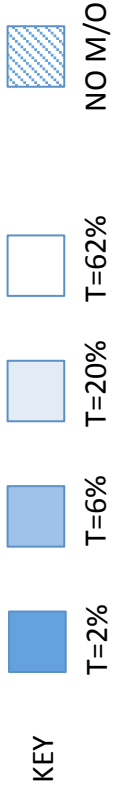


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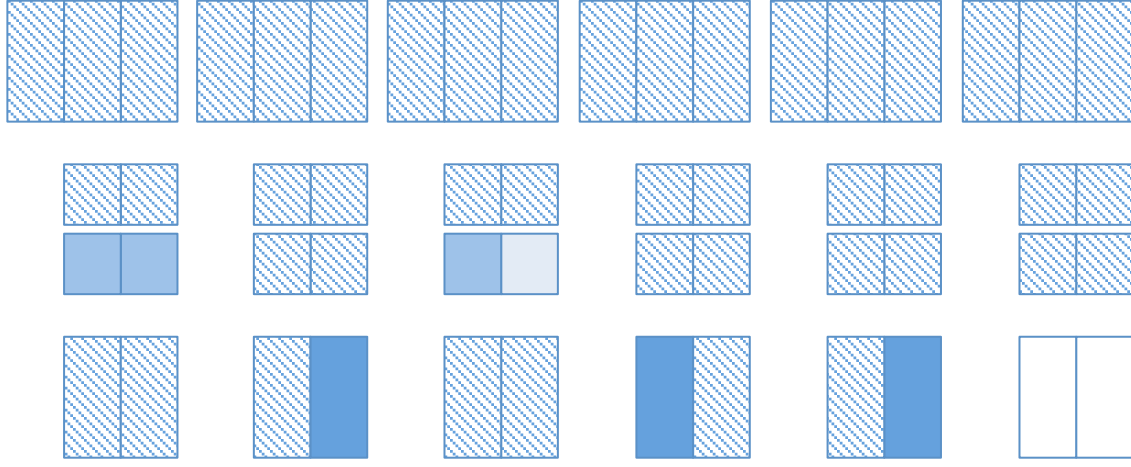
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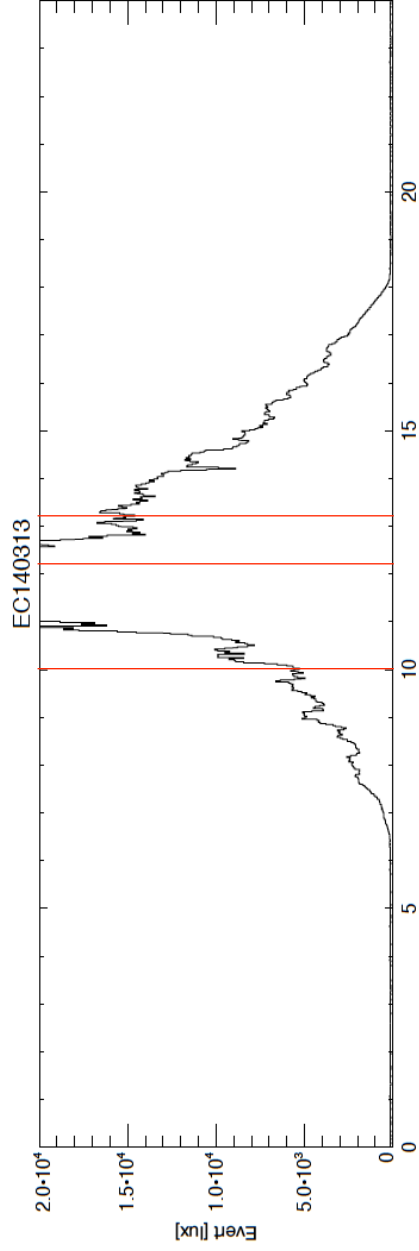
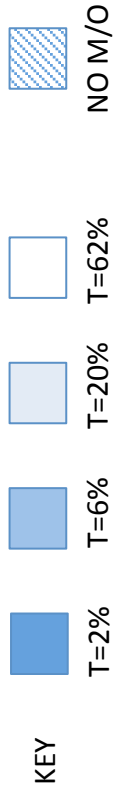
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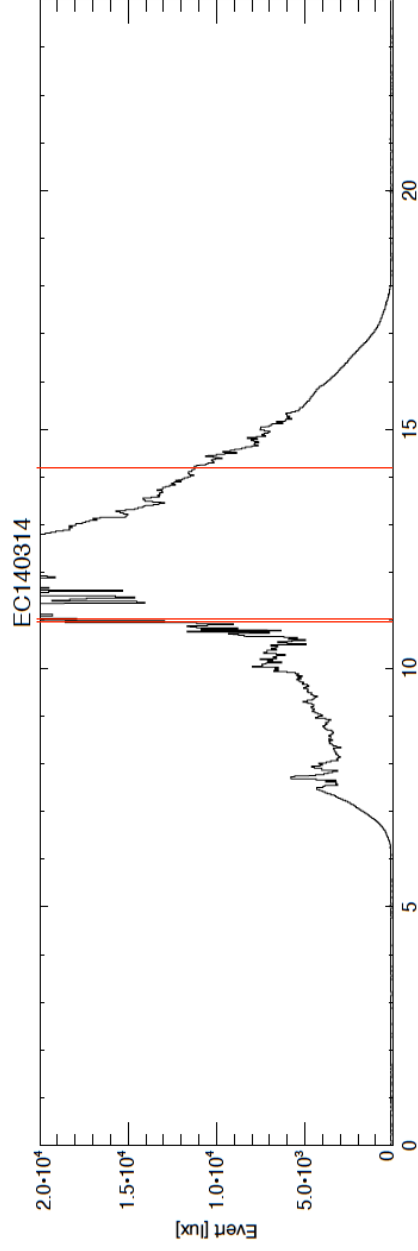




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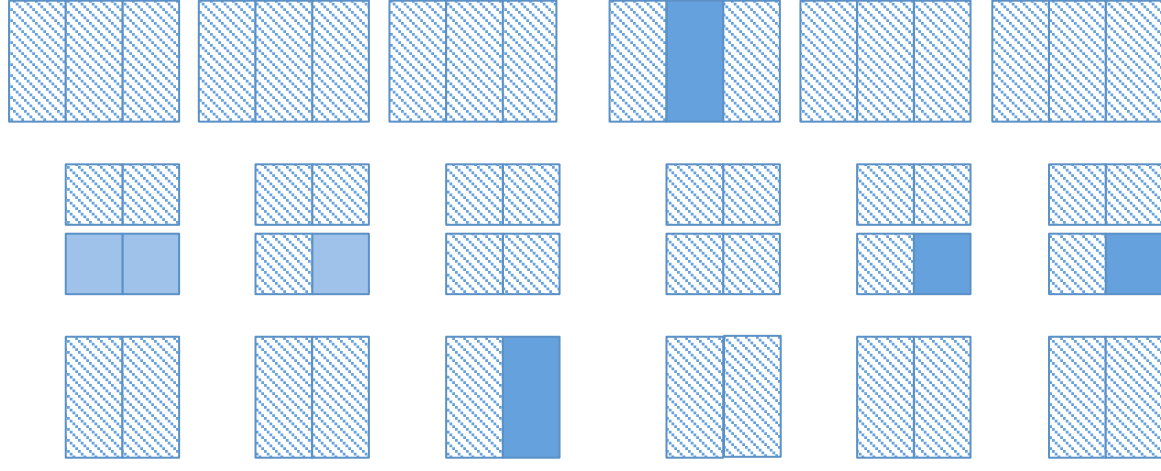
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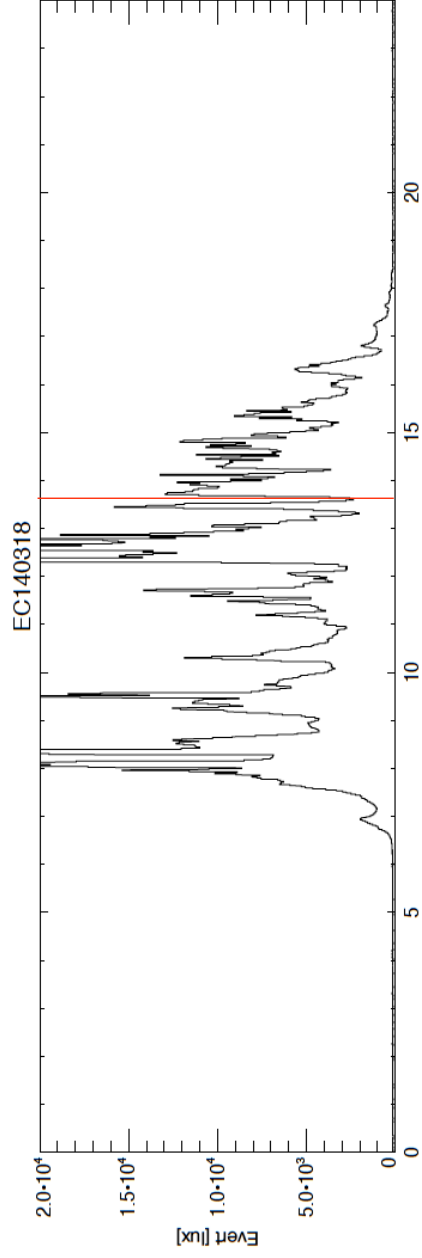
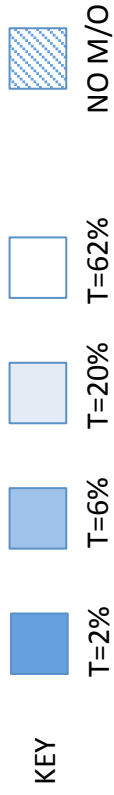


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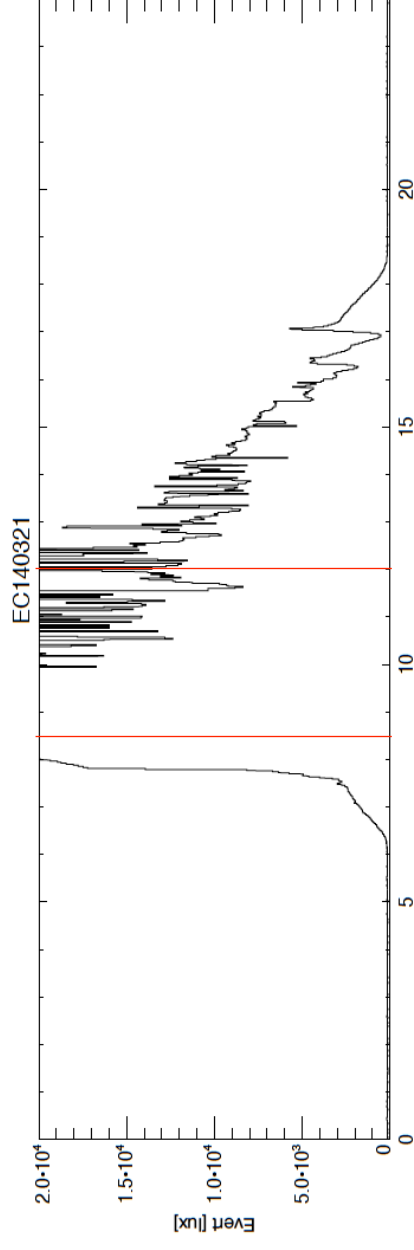
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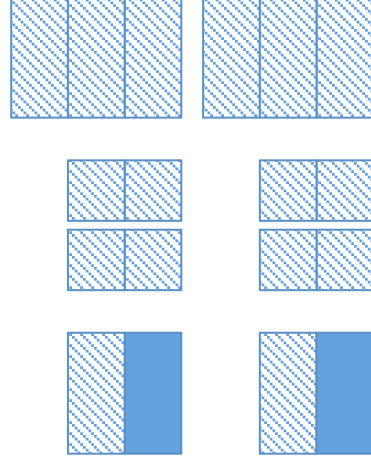




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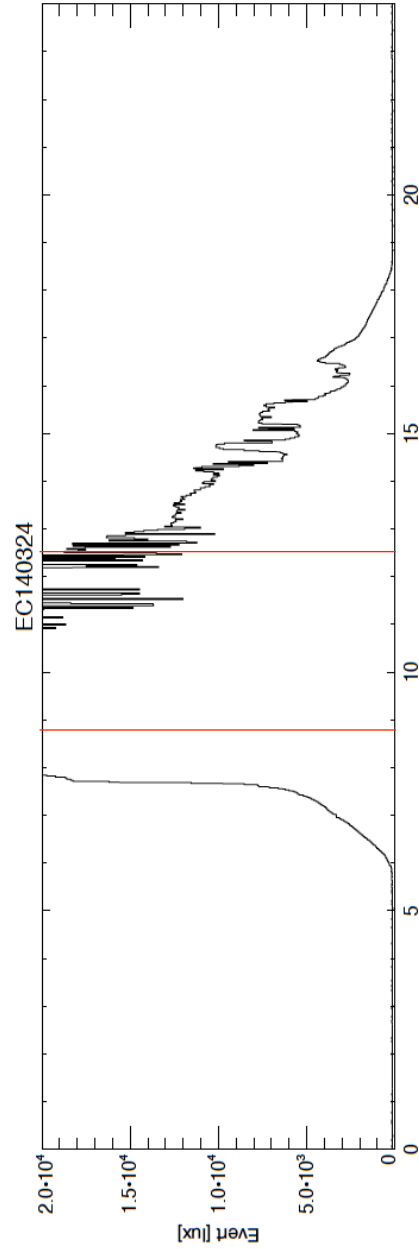
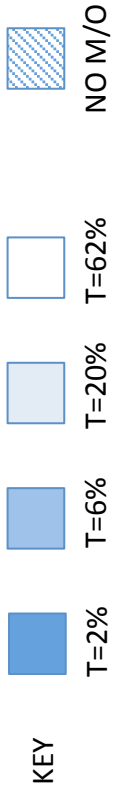


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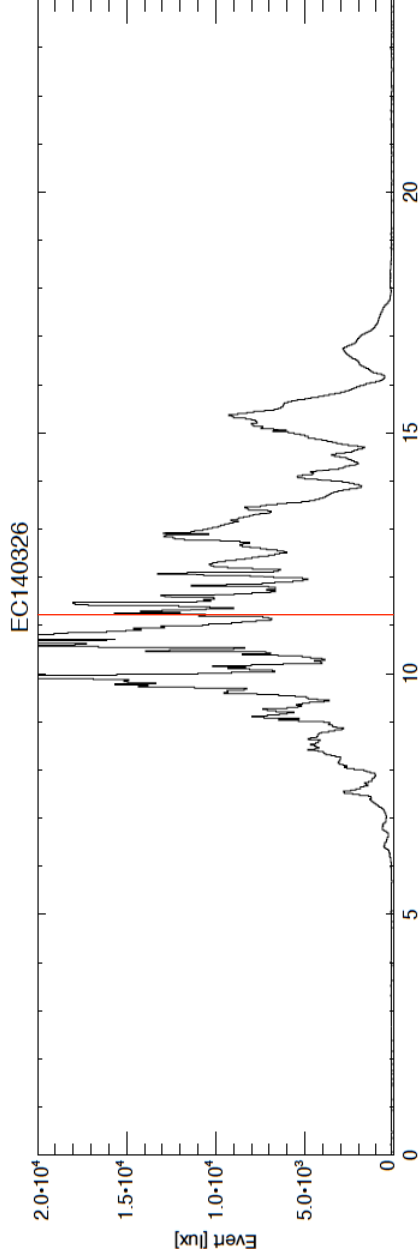
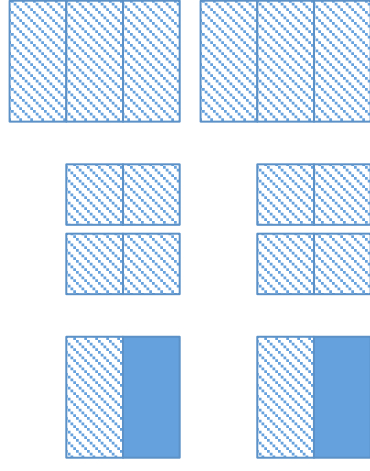
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08:47

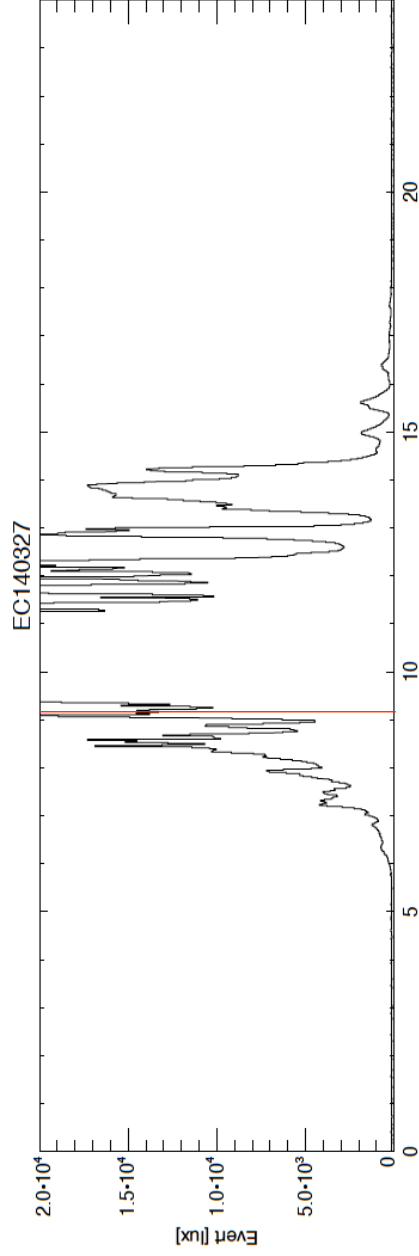
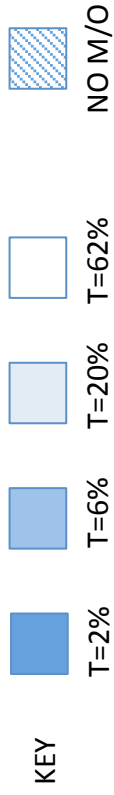
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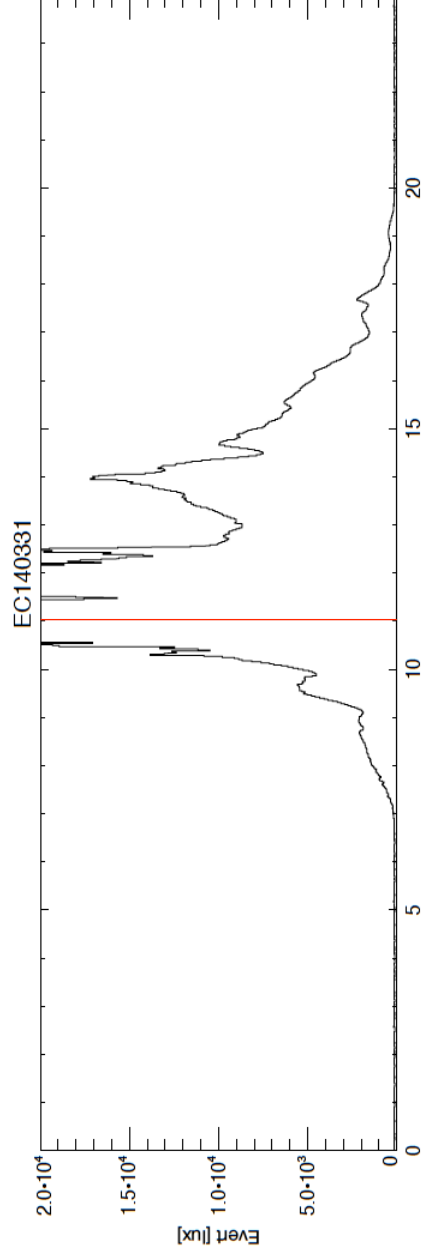
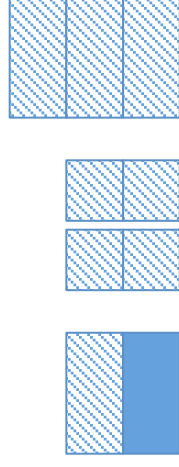
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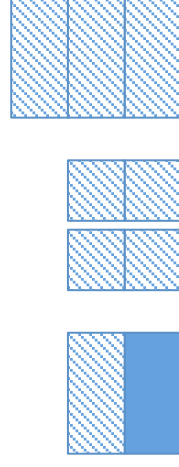


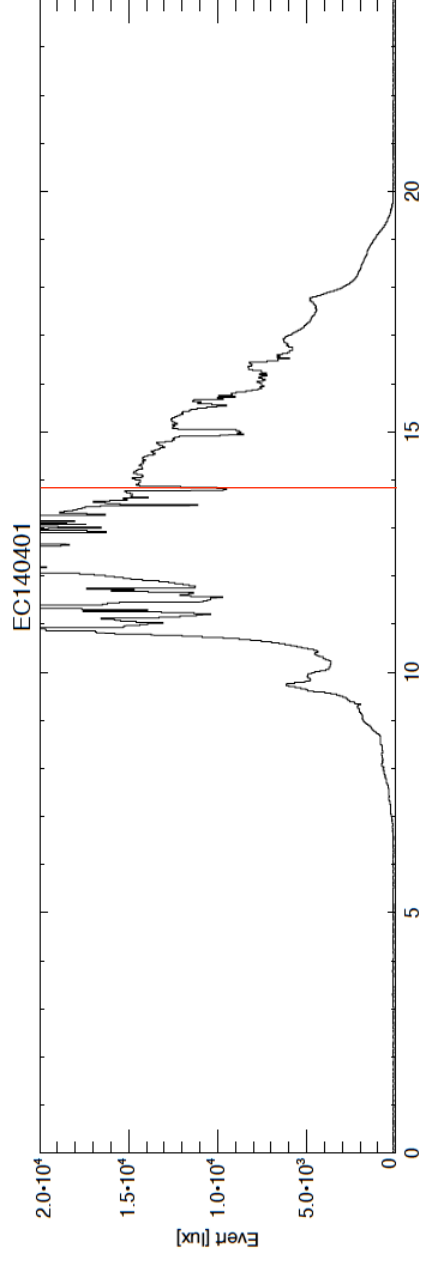
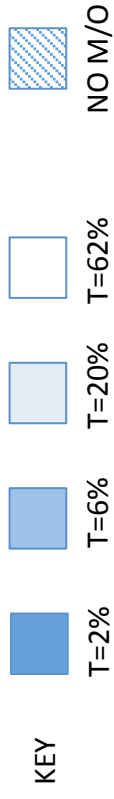


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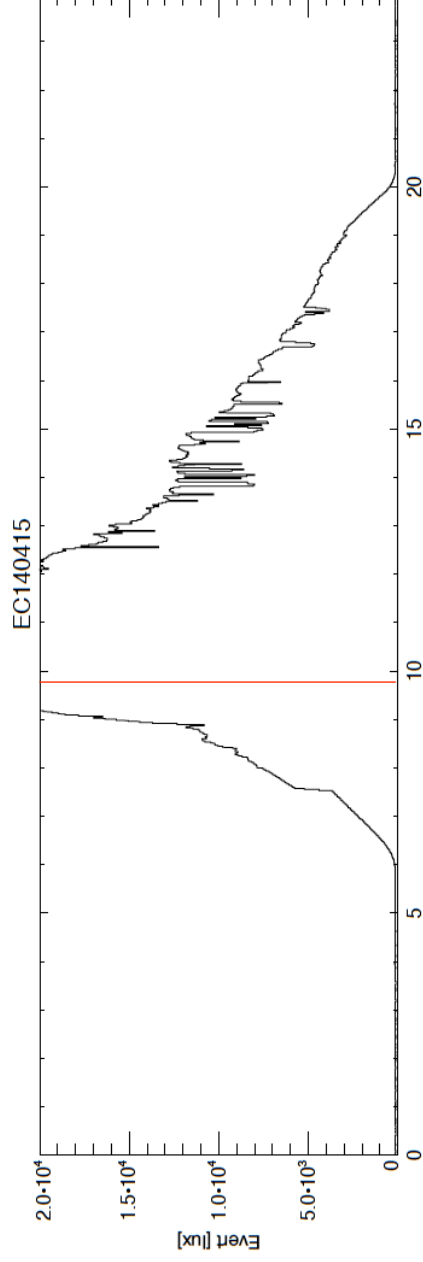
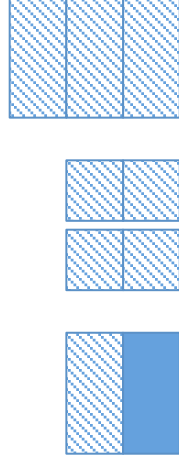


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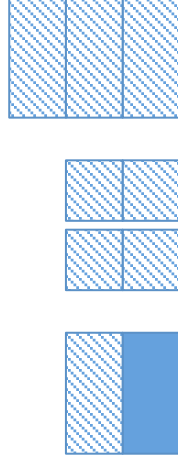


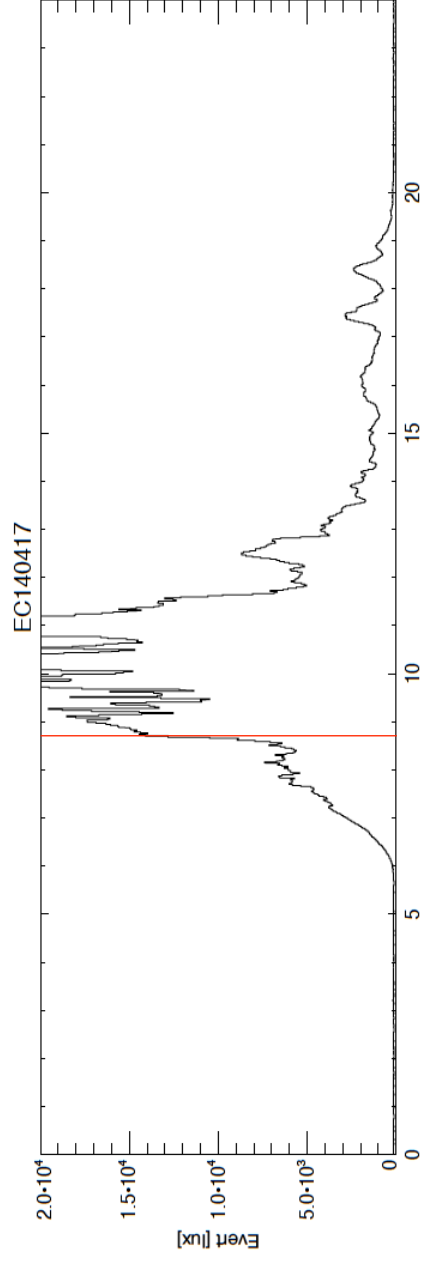
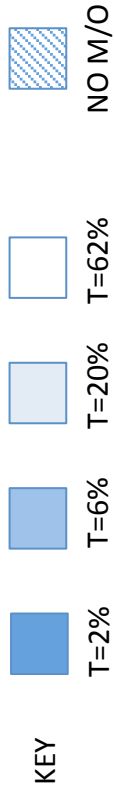


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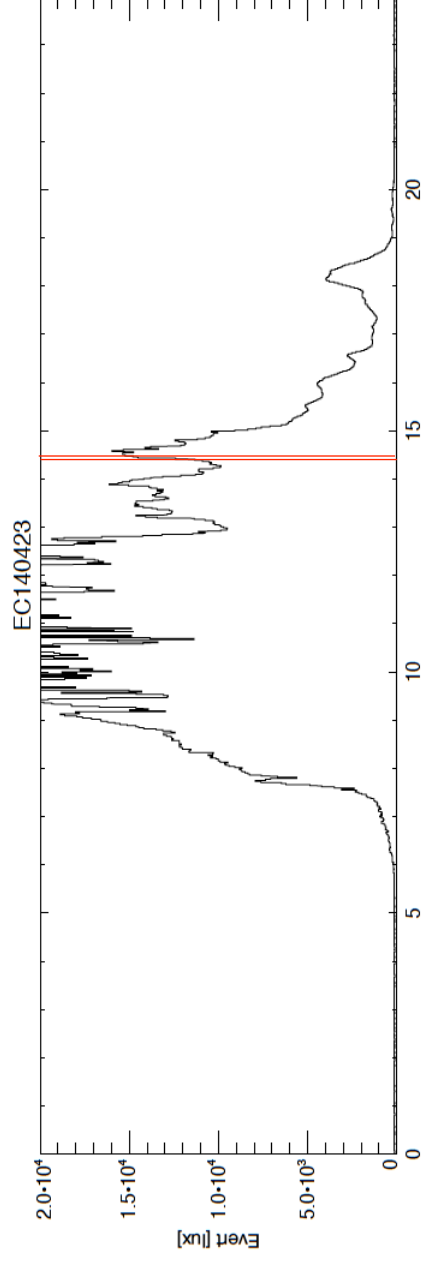
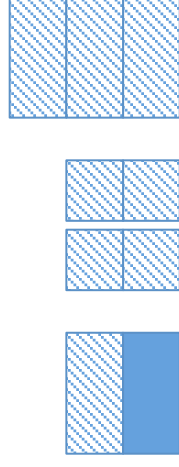


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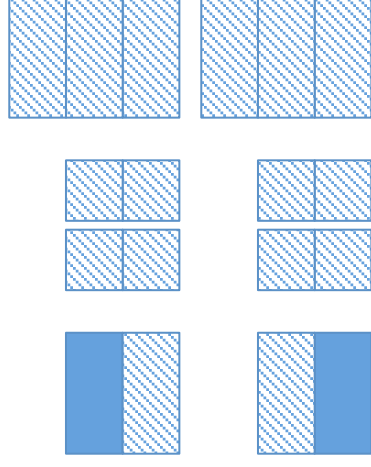




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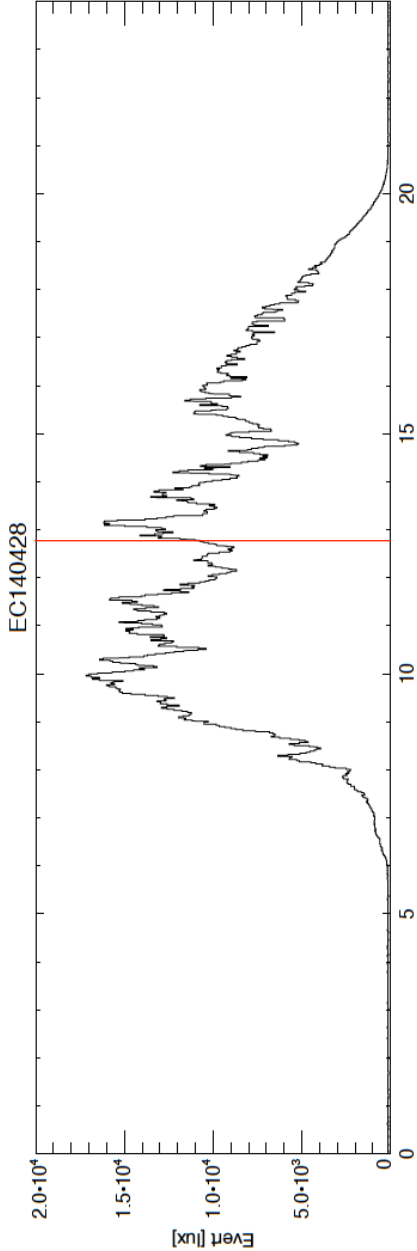
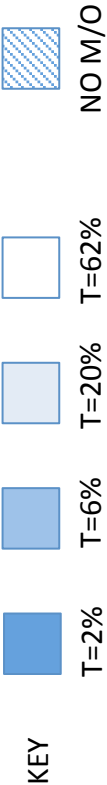


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14:30





12:51

